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THERMOPHILIC AEROBIC DIGESTION OF ORGANIC SOLID WASTES

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THERMOPHILIC AEROBIC DIGESTION OF ORGANIC SOLID WASTES

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The process of thermophilic aerobic digestion has been proposed to treat wastewater sludge, either alone or mixed with garbage. The major reactions involved in the process are presented, discussed, and simplified into an overall net reaction for the determination of the basic stoichiometric, thermochemical, and kinetic relationships. Volatile solids destruction, oxygen utilization, and carbon dioxide production are related stoichiometrically for both ammonia and nitrate as products of organic nitrogen oxidation. A simple procedure is presented for determining the thermochemistry of the net reaction by relating heat production to the oxygen equivalent or COD of the organic solids. The simulation studies and mathematical model discussed employ conservative values of biological parameters. The mathematical model provides assistance in planning and conducting pilot plant studies.

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

In an attempt to solve the problems involved in solid waste disposal, this report presents results obtained in an extensive study of the theoretical aspects of thermophilic aerobic digestion, a process utilized in the disposal of organic solid wastes through sewers.

A. W. Breidenbach, Ph.D.
Director
National Environmental
Research Center, Cincinnati

TABLE OF CONTENTS

	Page
INTRODUCTION	1
Possible Process Advantages	2
Scope of Study	4
BASIC THEORY	5
Reactions	7
Stoichiometry	11
Destruction of Organic Solids	11
Oxygen Utilization	15
Carbon Dioxide Production	17
Thermochemistry	18
Kinetics	23
Temperature and Kinetics	27
STEADY STATE MATHEMATICAL MODEL	29
Biodegradable Volatile Solids Balance	31
Oxygen Balance	34
Heat Balance	38
Heat Input from Mixing	39

Page

Biological Heat Production 39

Heat Loss in Effluent Sludge 41

Heat Loss as Latent Heat in Water Vapor 41

Heat Loss as Sensible Heat in Effluent Gas 42

Heat Loss to Surroundings 43

Summary 43

SIMULATION STUDIES 44

Isothermal Operation 46

Autothermal Operation 51

Air as Influent Gas 54

Nitrification 58

High Purity Oxygen as Influent Gas 61

DISCUSSION 65

SUMMARY AND CONCLUSIONS 67

GLOSSARY 70

REFERENCES 73

THERMOPHILIC AEROBIC DIGESTION OF ORGANIC SOLID WASTES

John F. Andrews[1]
and
Kawi Kambhu

INTRODUCTION

The collection, transport, processing, and disposal of organic solid wastes is a problem that has plagued man throughout the centuries. Moreover, there has been a great increase in both the magnitude and complexity of this problem during the past century because of man's tendency to concentrate in large metropolitan complexes.

The management of the organic solid wastes generated in a community is usually accomplished by two separate and quite distinct systems. One is the usual garbage collection service with collection and transport by motor vehicle and processing and disposal by incineration or land fill. The other is the water carriage system through which organic solids are transported by sewers to a wastewater treatment plant for separation and subsequent processing. There is an increasing tendency toward combining the two systems by grinding those organic solids normally collected by motor vehicle so that they can be added to the sewers. Individual home garbage grinders are widely used and many commercial establishments have also installed grinders. Some cities also use centrally located municipal grinding stations with addition of the ground garbage to the sewers or directly to the wastewater treatment plant.

The use of an existing transport system, the sewers, for garbage

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collection is a promising approach to the organic refuse problem. However, this means that increased emphasis must be placed on treatment of these organic solids once they have reached the wastewater treatment plant. The process proposed herein, thermophilic aerobic digestion, appears to have a significant potential for treatment of these organic solids.

One of the major factors to be considered in the use of a thermophilic process is the heat energy required to maintain thermophilic temperatures (120-140°F) and a cursory examination of the problem would tend to indicate that thermophilic aerobic digestion might not be economically feasible. However, heat can be produced by microbial thermogenesis as evidenced by the autothermal nature of composting processes which usually operate in the thermophilic temperature range. Also, in aerobic industrial fermentations (1) cooling coils are frequently necessary to remove the heat produced by thermogenesis and Wang (2) has indicated that the removal of excess heat is of considerable concern in the production of microbial protein from petroleum. Sufficient energy is generated to maintain thermophilic temperatures in the anaerobic digestion of wastewater sludges although in this instance it is produced as chemical energy (methane gas) which is subsequently converted to heat energy by combustion. The studies presented in this report show that sufficient heat energy can be generated in the aerobic digestion of organic solids so that the process is self-sustaining, with respect to temperature, in the thermophilic range.

Possible Process Advantages

The possible advantages of thermophilic aerobic digestion over the corresponding mesophilic process are:

1. Increased reaction rates for the destruction of organic solids.
2. Increased efficiency with respect to the fraction of organic solids destroyed.
3. Increased destruction of pathogenic microorganisms.
4. Improved solids-liquid separation.

Increased reaction rates at higher temperatures are normally reported in both the bacteriological and environmental engineering literature. Gaughran (3) has indicated that proteolysis, denitrification, and hydrolysis of starch by thermophilic bacteria proceed at rates seven to fourteen times that of cultures of mesophilic bacteria. Fair and Moore (4), among others, have shown that reaction rates are higher for thermophilic anaerobic digestion than for mesophilic anaerobic digestion. It is well known that as temperature increases, reaction rates increase for the activated sludge process, the trickling filter process, and stabilization ponds.

For a given residence time, thermophilic operation of a biological process should result in improved efficiencies with respect to the fraction of organic solids destroyed. Marr, Nilson, and Clark (5) have shown that the amount of substrate utilized for organism maintenance increases with temperature thus resulting in a lower yield of cellular mass (organic solids). Allen (6) has indicated that thermophilic bacteria have higher death rates and autolytic rates than mesophils. Increased destruction of lipids should result from their increased solubility at higher temperatures.

It is well recognized that increased destruction of pathogenic organisms occurs at higher temperatures and this is one of the key advantages of composting. Popova and Bolotina (7), in their discussion of the use of thermophilic (122°F) anaerobic digestion in Moscow (U.S.S.R.),

state that the greatest advantage of the process is the sanitary quality of the sludge. They reported the complete destruction of worm eggs at this temperature.

Improved solids-liquid separation is of importance in the dewatering of digested sludge for ultimate disposal. Although it is only one of many factors which affect solids-liquid separation, the decreased liquid viscosities at higher temperatures could improve separation. Gehn (8) has stated that the sludge from an activated sludge process operated at a temperature of 126°F had excellent settling characteristics. Garber (9) studied the vacuum filtration of thermophilic (122°F) anaerobic sludge and found that filter yields were 6.3 lb/sq ft/hr for the thermophilic process as compared to 1.7 lb/sq ft/hr for the mesophilic (84°F) process.

In comparing thermophilic aerobic digestion with other biological processes for the destruction of organic solids, such as anaerobic digestion, it should be noted that the thermophilic aerobic digestion process may have higher power requirements because of the necessity of supplying oxygen to the process. Also, at lower residence times the rate of destruction of organic solids may be limited by oxygen transfer capabilities. This rate limitation could be overcome by the use of high purity oxygen which also has the advantage of decreasing heat losses thus increasing the temperature at which the process will operate.

Scope of Study

The material presented in this report represents a portion of the results obtained in an extensive study of the theoretical aspects of thermophilic aerobic digestion which was financed by the Office of Solid Wastes, U. S. Public Health Service, from 1967 to 1971. Kambhu and

Andrews (10) have presented a preliminary mathematical model and simulation studies of the process which indicated that the process could be self-sustaining with respect to temperature. Kambhu (11), as a portion of the study, developed a fundamental model for the growth of mixed cultures of thermophilic microorganisms in a continuous-flow, complete-mixing reactor and experimentally determined the basic biological parameters for use in the model. Forty grams/liter of glucose were used as a substrate and temperatures and residence times investigated ranged from 113 to 149°F and 1 to 5 days, respectively. The results of another portion of the study will be reported by Matsche and Andrews (12) who studied the dynamics of continuous cultures of thermophilic microorganisms with emphasis on the effects of sudden changes in temperature.

The mathematical model and simulations studies presented herein are based on those previously presented (10, 11) using conservative values of the biological parameters as estimated from the literature. Simulations are presented for the use of either air or high purity oxygen as the influent gas for the biological oxidation of organic solids. Although the model should not be used for quantitative design or operation since it has not been verified in the field, the simulation results do indicate that the process has significant potential for the treatment of wastewater sludges, either alone or mixed with ground garbage, and pilot plant studies would be justified. The model should be of value in developing guidelines for these studies which should be performed prior to design and operation of full scale digesters.

BASIC THEORY

From a microbiological viewpoint, the thermophilic aerobic digestion process may be classified as a continuous-flow, enrichment culture

of thermophilic microorganisms with the predominating species being determined by the characteristics of the input wastes and the environmental conditions created through process design and operation. Sufficient heat can be generated through thermogenesis so that the process is self-sustaining with respect to temperature and may therefore be classified as an autothermal process.

Although the process is simple in concept, in reality it is a highly complex biological system with poorly understood behavior. A systematic approach is therefore needed in the development of a mathematical model of the process. The first step is to identify the major reactions involved. These may be roughly classified as solubilization of the organics in the influent, growth of thermophilic microorganisms, and subsequent autooxidation of the thermophils which have been produced. Once the significant reactions have been established, the stoichiometry and thermochemistry must be determined. Knowledge of the stoichiometry is necessary to calculate the amount of organic solids destroyed and the oxygen requirements. A knowledge of the thermochemistry is needed to calculate the heat generated through thermogenesis which, when combined with the heat losses, determines the temperature at which the process can be operated without an external supply of heat. The basic kinetic relationships must then be determined. For a new process, such as thermophilic aerobic digestion, it appears reasonable as a first approximation to express the rate of destruction of organic solids as first order with respect to the concentration of biodegradable organic solids in the reactor. The kinetic coefficient and other temperature dependent parameters must be expressed as functions of temperature. In establishing the stoichiometry, thermochemical, and kinetic relationships it must be remembered that these can be greatly influenced by environmental

variables such as pH, ionic environment, toxic materials, etc.

Reactions

The reactions involved in thermophilic aerobic digestion are illustrated in Figure 1. The organic solids which serve as substrate for the thermophilic microorganisms may consist of a wide variety of organic materials and Allen (6), in her 1953 literature review of the thermophilic aerobic sporeforming bacteria, indicated that the oxidative capacities of the thermophils, with respect to variety of substrates utilized, were at least as great as those of the mesophils. Among the substances which have been utilized by the thermophils are cellulose, lipids, proteins, sugars, alcohols, aromatic compounds, purines, and carboxylic acids. A small fraction of the organic solids found in sewage sludges and garbage will consist of thermophilic microorganisms and can serve as an inoculum for process start-up. In this respect it should be noted that Gaughran (3), in his 1947 literature review of the thermophilic bacteria, indicates that they have been isolated from a great variety of sources including the alimentary canal of man and animals. Kambhu (11) was easily able to start continuous-flow thermophilic cultures using domestic sewage as an inoculum.

Solid organics cannot pass through the cell membrane of microorganisms and must be solubilized before they can be metabolized. This can be accomplished by the excretion of extracellular enzymes, liberation of intracellular enzymes by cell lysis, or breakdown by cell contact (13). Rates of solution or mass transfer into the cell could therefore limit the rate of destruction of volatile solids. However, since many organic compounds, and especially lipids, are more soluble at higher temperatures, it would be expected that transport rates would

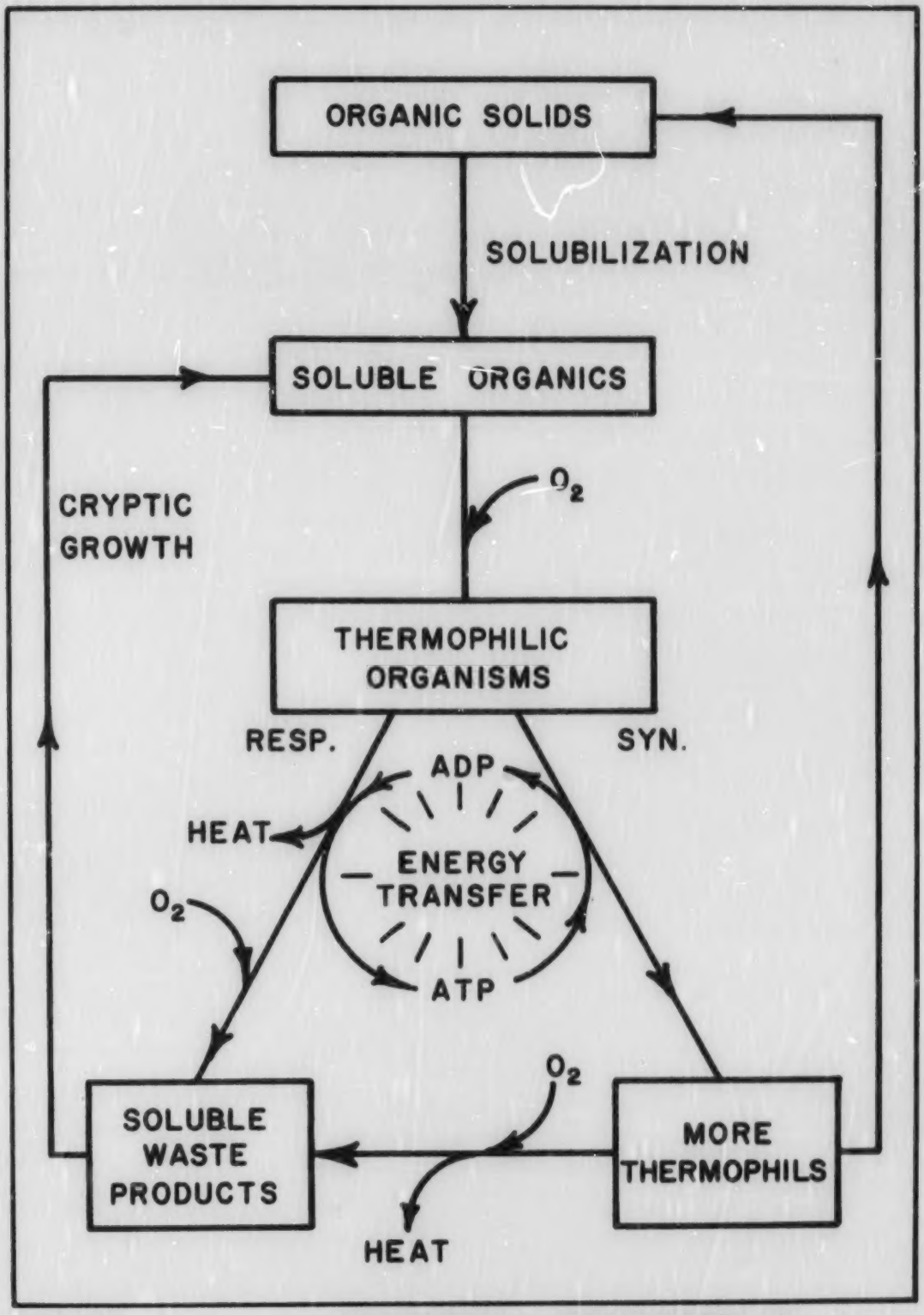

FIGURE 1. BIOLOGICAL REACTIONS IN THERMOPHILIC AEROBIC DIGESTION

increase as temperature increases. For this same reason, it would also be expected that a higher fraction of the organic solids in wastewater sludge and ground garbage would be classified as biodegradable at thermophilic temperatures.

Once the soluble organics, along with oxygen as a hydrogen acceptor, are transported into the cell, metabolism occurs with the organics being converted to waste products (respiration) and more thermophilic microorganisms (synthesis). The need for oxygen also raises the possibility of overall rate control by mass transfer of oxygen from the gas to the liquid phase. When the oxygen supply rate is adequate, the major products of respiration would be carbon dioxide, water, and ammonia although at longer residence times microorganisms could develop which will convert the ammonia to nitrate as occurs in mesophilic aerobic digesters, the activated sludge process, and trickling filters. At the higher temperatures of thermophilic aerobic digestion, the possibility also exists of significant transfer of ammonia from the liquid to the gas phase.

Respiration is an exergonic reaction and a portion of the energy released in this reaction is stored in the form of high energy compounds such as adenosine triphosphate (ATP) which serve to drive the synthesis reactions involved in the production of more microorganisms, Since microorganisms are not 100 percent efficient in transferring energy from respiration to synthesis, some of the energy produced in respiration is liberated as heat energy. The efficiency of coupling between respiration and synthesis has frequently been assumed constant (14, 15) thus permitting a calculation of the yield of microorganisms from the free energy available in oxidation of the substrate. However, the efficiency of coupling can vary with the species of microorganisms and environmental conditions. For example, Senez (16) has discussed instances in which

synthesis and respiration can be almost completely uncoupled by temperature increases or by leaving some essential nutrient, such as nitrogen, out of the medium. The excess energy provided through substrate respiration is then dissipated as heat or stored by the microorganisms as chemical energy in such compounds as glycogen, polyhydroxybutyrate, or ATP. The observed efficiency of coupling can also be affected by the use of a fraction of the energy produced to provide energy for maintenance of the existing microbial population (17). The energy of maintenance is that portion of the substrate energy used to provide energy to maintain existing cellular materials and is not available for synthesis. It is a function of both time and the concentration of existing microorganisms and has been shown by Marr, et al (5) to also be a strong function of temperature.

The microorganisms produced undergo organism decay (endogenous respiration or death with subsequent lysis) which results in a decrease in organism mass. Oxygen will be consumed in this reaction and heat will be produced. It is expected that organism decay would occur at significantly higher rates for thermophils than for mesophils. Allen (6) has indicated that cell material is rapidly destroyed during growth of thermophils and that cultures of thermophilic bacteria contain appreciable amounts of lysis products even during the early phases of growth. Because of both higher organism decay rates and higher requirements for maintenance energy, observed yields of thermophilic microorganisms are usually considerably lower than those for mesophils. Both soluble and insoluble waste products would result from organism decay and some of these would not be biodegradable.

Additional microorganisms could grow on both the soluble and insoluble products of organism decay as indicated by the feedback loops shown

in Figure 1. This is known as cryptic growth and could be of considerable significance for mixed cultures of thermophilic microorganisms where organism decay rates are high and several microbial species can be present. Postgate and Hunter (18), working with pure cultures of Aerobacter aerogenes at mesophilic temperatures, have found a maximum cryptic growth of approximately one new organism at the expense of about 47 dead ones.

Stoichiometry

From the previous discussion it is readily apparent that the aerobic digestion of organic solids is a complex process involving many reactions. Consideration of all of the reactions presented in Figure 1 would not only result in a model cumbersome to use but would also involve the use of many parameters which cannot be adequately measured in the field. For example, the volatile solids test, currently used for digester design and control, cannot adequately distinguish between microorganisms and their substrates since both are reflected in the test results. For the purposes of this investigation, the reactions presented in Figure 1 have therefore been simplified into an overall net reaction as shown in Equation 1 and it is the purpose of this section to establish the stoichiometric relations between the reactants and products.

$$\text{Total Organic Solids} + O_2 \xrightarrow[\text{Nutrients}]{\text{Microorganisms}} \text{Non-biodegradable Organic Solids} + CO_2 + H_2O + NH_4^+ \text{ or } NO_3^- \quad (1)$$

Destruction of Organic Solids. The concentration of volatile solids (VS) is used as an index of the total organic solids in the feed to a digester and the fraction of the total solids which are volatile (F_{VS}) may range from 0.5 to 0.9 depending on the source and previous processing of the solids. The volatile solids may be further classified as bio-

degradable (BVS) and nonbiodegradable (NBVS) volatile solids. The fraction of the volatile solids which are biodegradable (F_{BVS}) would, as for the volatile solids in the feed, depend on source and previous processing but, in addition, would also depend upon the conditions under which the reactions occur in the digester. Relatively few investigators have reported values for F_{BVS} and for this reason it must usually be estimated from the fractions of volatile solids destroyed after specified digestion times as given in Table I. Although these are not equivalent to F_{BVS} (which would be approached as time approaches infinity), the results presented for the longer digestion times should serve as reasonable approximations.

F_{BVS} would be expected to be a function of temperature for several reasons among these being the increased solubility of many organics, lower yields of thermophilic microorganisms, higher substrate utilization rates for maintenance energy, and higher organism decay rates at higher temperatures. The effects of temperature on some of these parameters for mixed cultures of thermophils grown on a soluble substrate are illustrated in Table II from Kambhu (11). The negative value obtained for the specific maintenance coefficient at 149°F is probably due to the additional substrate supply made available for maintenance through organism decay thus indicating the significance of organism decay and also cryptic growth at thermophilic temperatures. An increase in F_{BVS} with temperature can be considered analogous to the increase in first stage biochemical oxygen demand (BOD) which occurs with increasing temperature since the reactions illustrated in Figure 1 also take place in the BOD test. Although it is clear that F_{BVS} should be a function of temperature, this relationship cannot be adequately defined or even empirically estimated at this time and F_{BVS} has therefore been assumed

TABLE I

ESTIMATION OF BIODEGRADABLE VOLATILE SOLIDS

Material	Fraction Volatile Solids Destroyed	Digestion Time Days	Temp. °F.	Reference & Comments
Primary and waste activated sludge from domestic sewage	0.46	60	63	Jaworski, et al (19) Reactor fed daily
	0.45	10	95	
Textile and domestic sewage	0.60	-	-	Barnhart (20) Estimated F_{BVS}; Feeding rate not reported
Pharmaceutical waste	0.75	-	-	Barnhart (20) Estimated F_{BVS}; Feeding rate not reported
Primary and waste activated sludge from domestic sewage	0.53	30	68	Lawton and Norman (21) Reactor fed daily
Night Soil	0.46	20	108	Reyes and Kruse (22) Batch reactor
	0.51	20	122	
	0.67	20	140	
Waste activated sludge from domestic sewage (Biosorption Process)	0.46-0.55	-	-	Reynolds (23) Batch reactor
Ground garbage, digested sludge, and waste paper (Mechanical Compost Unit)	0.45	18	152	Schulze (24) Reactor fed daily
Primary sludge from domestic sewage	0.68	92	Ambient	Rudolfs & Heukelekian (25) Batch reactor

TABLE II

BIOLOGICAL PARAMETERS FOR MIXED CULTURES OF THERMOPHILIC MICROORGANISMS (11)

Temperature ^{o}F	Yield Coefficient Gm/Gm	Organism Decay Rate $Days^{-1}$	Maintenance Coefficient $Days^{-1}$
113	0.34	0.08	0.44
122	0.36	0.10	0.42
131	0.32	0.13	0.74
140	0.29	0.21	0.79
149	0.10	0.33	-2.63

The yield coefficient is expressed as mass of organisms produced/mass of substrate utilized and is corrected for organism decay and substrate utilized for maintenance energy.

The organism decay coefficient is expressed as mass of organisms destroyed/mass organisms present/day and is corrected for substrate utilization for maintenance energy.

The maintenance coefficient is expressed as mass of substrate utilized for maintenance energy/mass organisms present/day.

constant at a value of 0.70 throughout this study. The material which has been presented in this paragraph should be considered as qualitative evidence to justify the use of a higher value of F_{BVS} for thermophilic as opposed to mesophilic aerobic digestion and therefore a higher possible destruction of volatile solids in thermophilic processes.

Equation 1 may now be rewritten as shown below where the total organic solids term is replaced with a biodegradable volatile solids (BVS)

$$\text{Biodegradable Volatile Solids} + O_2 \xrightarrow[\text{Nutrients}]{\text{Microorganisms}} CO_2 + H_2O + \begin{matrix} NH_4^+ \\ \text{or} \\ NO_3^- \end{matrix} \qquad (2)$$

term which is equal to $(F_{BVS})(VS)$ or $(F_{BVS})\ (F_{VS})(TS)$. The NBVS need not be shown in the reaction since these solids can be considered as inert material not affected by the reaction. However, it should be clearly understood that F_{BVS}, as used in this report, applies only to the feed sludge since this fraction will change throughout the course of the reaction as BVS changes with NBVS remaining constant.

Oxygen Utilization. Another key item which must be known in order to establish the stoichiometry is the ratio of oxygen utilized to volatile solids oxidized, $(OE)_C$. The numerical value for $(OE)_C$ is greatly dependent upon the composition of the solids as illustrated by the fact that $(OE)_C$ for the oxidation of organic compounds may range from four lbs of oxygen per lb of methane oxidized to almost zero for those organic compounds just slightly more reduced than carbon dioxide. Values of $(OE)_C$ can be calculated if the elemental composition of the solids is known and are given for several organic compounds in Table III. A typical calculation for the oxidation of microorganisms with an empirical composition of $C_5H_7NO_2$ (26) is given below:

$$C_5H_7NO_2 + H^+ + 5\,O_2 \longrightarrow 5\,CO_2 + 2\,H_2O + NH_4^+ \quad (3)$$

m.w. = 113

The oxygen equivalent of these microorganisms is equal to (5 x 32)/(113) or 1.42 lbs of oxygen/lb of microorganisms oxidized.

The calculation of $(OE)_C$ by writing and balancing the oxidation-reduction reaction requires an elemental analysis; however, equipment for this analysis is usually not available in wastewater treatment plant laboratories and, if available, would require the services of a skilled technician. Fortunately, $(OE)_C$ can normally be assumed equal to the chemical oxygen demand (COD) of the waste when this is expressed in units of lbs of COD/lb of VS, and equipment for the COD test is found in most wastewater treatment plant laboratories. Kambhu (11) has reported COD values for thermophilic microorganisms grown on glucose at several residence times to be 1.57, 1.58, 1.63, 1.65, and 1.62 lbs O_2/lb VS for temperatures of 113, 122, 131, 140, and 149° F, respectively. Malina and Burton (27), in their study of the aerobic digestion at 95° F of primary sludge from domestic sewage reported COD values of 1.52 and 1.44 lbs O_2/lb of VS in the feed and effluent sludge, respectively.

If the reaction is allowed to proceed for a sufficient length of time, microorganisms may develop which can convert ammonia to nitrate as given in Equation 4. The oxygen required to carry out this reaction,

$$NH_4^+ + 2\,O_2 \longrightarrow H_2O + 2\,H^+ + NO_3^- \quad (4)$$

$(OE)_N$, would be equal to (2 x 32)/(14) or 4.56 lb of oxygen/lb of ammonia expressed as nitrogen. When Equations 3 and 4 are added, the net equation is:

$$C_5H_7NO_2 + 7\,O_2 \longrightarrow 5\,CO_2 + 3\,H_2O + NO_3^- + H^+ \quad (5)$$

m.w. = 113

The total oxygen requirement, as given in Equation 5, includes both the carbonaceous, $(OE)_C$, and nitrogenous, $(OE)_N$, oxygen demand and is equal to (7 x 32)/(113) or 1.98 lbs of oxygen/lb of microorganisms oxidized. This represents a substantial increase over the carbonaceous oxygen demand which is 1.42 lbs/lb. $(OE)_C$ may still be assumed equal to the COD of the organic solids since the product of organic nitrogen in the COD test is ammonia (28). Values for $(OE)_N$ may be calculated by multiplying the fraction of nitrogen, F_N, in the biodegradable volatile solids by (2 x 32)/(14) or 4.56.

The amount of oxygen required for the oxidation of BVS in Equation 2 can be calculated as $(OE)_C(BVS)$ when the product of organic nitrogen is ammonia or as $(OE)_C(BVS) + (4.56)(F_N)(BVS)$ when the product is nitrate.

Carbon Dioxide Production. Knowledge of the gas flow rates into and out of an aerobic digester are needed in order to make a heat balance on the digester. The ratio of the volume of carbon dioxide produced to the volume of oxygen utilized is known as the respiratory quotient (RQ) and is approximately equal to 1.0 for the mixture of organics found in domestic wastewater when the nitrogen in the solids is converted to ammonia. The volumetric flow rate of the dry gas out of the reactor will be less than that into the reactor since a portion of the carbon dioxide produced will remain dissolved in the liquid phase while still another portion will be converted to bicarbonate. However, the difference between the volumetric flow rates of gas into and out of the reactor should be negligible for the COD values and oxygen transfer efficiencies to be used in this report which result in a relatively high ratio of gas flow rate to liquid flow rate. In any event, this is a conservative assumption since it results in higher heat losses from the reactor. On

a mass basis, (44/32) or 1.38 lbs of carbon dioxide would be produced for each pound of oxygen utilized and the mass flow rate of dry gas out of the reactor would exceed the mass flow rate of dry gas into the reactor.

As shown in Equation 4, carbon dioxide is not produced in the oxidation of ammonia to nitrate although oxygen is consumed. The volumetric flow rate of dry gas into the reactor would therefore be greater than the volumetric flow rate out of the reactor. However, the mass of carbon dioxide produced would still be equal to $(44/32)(OE)_C$ and this, plus a knowledge of the oxygen transfer efficiency and amount of ammonia oxidized can be used to calculate the mass flow rate of dry gas into and out of the reactor.

Thermochemistry

Significant amounts of heat energy can be generated in biological processes and the amount of heat produced can be calculated by applying the principles of thermochemistry to the stoichiometric equations. The reactions represent biological instead of physical combustions and heats of reaction are therefore equal to heats of combustion. Published heats of combustion are on a constant volume and temperature basis instead of a constant pressure and temperature basis as exists in most biological systems; however, as shown by Scott (29), the correction for this is small and can usually be neglected. A correction is necessary for the product of combustion of organic nitrogen since published values are for nitrogen gas as a product whereas in aerobic biological systems the product may be either ammonia or nitrate.

For known organic compounds, heats of combustion can be obtained from published data such as that presented in the Handbook of Chemistry

and Physics (30). However, this is not possible for the unknown mixtures of organics found in organic solid wastes or wastewater sludges. If the elemental composition of the mixture is known, heats of combustion can be calculated using the empirical equation developed by Spoehr and Milner (31) which is presented below. In developing this equation, Spoehr and Milner assumed the products of combustion to be gaseous carbon dioxide, liquid water, and nitrogen gas.

$$h = 127\,R + 400 \tag{6}$$

$$R = \frac{100\,[2.66(\%C) + 7.94\,(\%H) - (\%O)]}{398.9} \tag{7}$$

where:

h = heat of combustion, calories/gram

R = degree of reduction

The percentages of carbon, hydrogen, and oxygen used in Equation 7 are on an ash free basis and the calculated heat of combustion therefore represents the volatile fraction of the total solids. Heats of combustion could also be obtained analytically using a calorimeter. However, both of these methods for determining heats of combustion require the use of analytical instrumentation normally not available in wastewater treatment plant laboratories. Corrections would also be necessary for the products of combustion of organic nitrogen.

A promising technique for estimating heats of combustion from readily available analytical techniques is suggested by the work of Mayberry, et al (32, 33) in which they related heats of combustion to the number of electrons transferred to oxygen when organic compounds, including microorganisms, are theoretically oxidized to gaseous carbon dioxide, liquid water, and nitrogen gas. They found the heat of combustion per gm-electron to be relatively constant for a variety of organic compounds and

related this to the mass of oxygen utilized since each molecule of oxygen can accept four electrons. Heats of combustion can therefore be related to oxygen utilization as expressed in Equations 3 and 5 if corrections are made for the differences in the products of organic nitrogen. Values of the heats of combustion expressed as BTU/lb $(OE)_C$ are presented in Table III for several organic compounds. The values presented have been corrected for ammonia as a product instead of nitrogen gas and range from 5,750 to 6,500 BTU/lb $(OE)_C$ with an average of 6,100 BTU/$(OE)_C$ which will be used throughout this study. An example of the calculations involved in preparing Table III, using alanine, is given below.

$$(C_3H_7NO_2)_s + 3.75(O_2)g \longrightarrow 3(CO_2)_g + 3.5(H_2O)_{aq} + 0.5(N_2)_g \quad (8)$$

$$(NH_4^+)_{aq} + 0.75(O_2)_g \longrightarrow (H^+)_{aq} + 1.5(H_2O)_{aq} + 0.5(N_2)_g \quad (9)$$

$$(C_3H_7NO_2)_s + 3(O_2)_g + (H^+)_{aq} \longrightarrow 3(CO_2)_g + 2(H_2O)_{aq} + (NH_4^+)_g \quad (10)$$

The net reaction, Equation 10, is obtained by subtracting Equation 9 from Equation 8. The heat of combustion for the net reaction is obtained in the same fashion and is equal to (-387.7) - (-70.7) or -317.0 Kcal/gm-mole of alanine which is equivalent to 5,950 BTU/lb $(OE)_C$. As previously noted, $(OE)_C$ can normally be assumed to be equal to the COD and equipment for this analysis is available in most wastewater treatment plant laboratories.

The average value of 6,100 BTU/lb of $(OE)_C$ compares favorably with that reported by other investigators. Cooney, et al (34) correlated oxygen consumption with heat evolution for different microorganisms grown at several rates using different substrates and found that 0.11 ± 0.01 Kcal of heat was produced for each millimole of oxygen consumed

TABLE III

HEATS OF COMBUSTION FOR ORGANIC COMPOUNDS

Substance	$(OE)_C$ $\frac{lb\ O_2}{lb\ sub}$	Heat of Combustion		Remarks
		$\frac{BTU}{lb\ sub}$	$\frac{BTU}{lb\ (OE)_C}$	
Microorganisms ($C_5H_7NO_2$)	1.42	9,210	6,500	Calculated by method of Spoehr & Milner (31)
Microorganisms ($C_4H_8NO_2$)	1.33	8,230	6,160	Calorimeter analysis by Mayberry, et al (33)
Alanine ($C_5H_7NO_2$)	1.08	6,400	5,950	a
Glycine ($C_2H_5NO_2$)	0.64	3,930	6,150	a
Glycelglycine ($C_4H_8N_2O_3$)	0.73	4,500	6,190	a
Glucose ($C_6H_{12}O_6$)	1.07	6,760	6,350	a
Arabinose ($C_5H_{10}O_5$)	1.07	6,720	6,300	a
Glycerol ($C_3H_8O_3$)	1.22	7,760	6,350	a
Phenol (C_6H_6O)	2.38	14,000	5,890	a
Succinic acid ($C_4H_6O_4$)	0.95	5,450	5,750	a
Acetic acid ($C_2H_4O_2$)	1.07	6,290	5,890	a
Palmitic acid ($C_{16}H_{32}O_2$)	2.88	16,850	5,860	a
Citric acid ($C_6H_8O_7$)	0.75	4,450	5,900	a
Ethanol (C_2H_6O)	2.09	12,840	6,150	a
Butanol ($C_4H_{10}O$)	2.60	15,420	5,900	a
Methane (CH_4)	4.00	23,700	5,940	a

[a]Heats of combustion obtained from Handbook of Chemistry and Physics (30) and corrected to products of combustion as $(CO_2)_g$, $(H_2O)_{aq}$, and $(NH_4^+)_{aq}$.

which is equivalent to 6,200 BTU/lb of oxygen utilized. Rothbaum and Stone (35) studied the heat output of E. coli grown on several different media and found a heat production of 6,480 BTU/lb of oxygen consumed. Kambhu (11) determined both the heats of combustion and COD's of thermophilic microorganisms grown on glucose at temperatures ranging from 113 to 149° F and several residence times and found a mean value of 5,860 BTU/lb of organism COD.

The amount of heat produced through biological action in Equation 2 can now be calculated as 6,100 $(OE)_C(BVS)$ when ammonia is the product of organic nitrogen oxidation. If ammonia is converted to nitrate, additional heat will be produced by the reaction shown below.

$$(NH_4^+)_{aq} + 2\,(O_2)_g \longrightarrow (NO_3^-)_{aq} + (H_2O)_{aq} + 2\,(H^+)_{aq} \qquad (11)$$

The heat of combustion for Equation 11 is -86 Kcal/gm-mole of ammonia which corresponds to 11,000 BTU/lb of ammonia expressed as nitrogen. The heat produced in Equation 2 with nitrate as a product can now be calculated as 6,100 $(OE)_C(BVS)$ + 11,000 $(F_N)(BVS)$.

Fair and Moore (36) have conducted an extensive survey of the fuel value of sewage sludges and the values reported by them can be used to justify the relationships which have been proposed between volatile solids, oxygen equivalents, and heats of combustion. Table IV gives heats of combustion reported by Fair and Moore for both primary and waste activated sludge for different values of F_{VS}. Values of $(OE)_C$ have been calculated assuming that 6,100 BTU of heat is produced per lb of $(OE)_C$ and that the sludges contain 5 percent (w/w) nitrogen. The calculated values of $(OE)_C$ range from 1.42 to 1.96 thus indicating that the value of $(OE)_C$ to be used in this report (1.5 lb O_2/lb VS) is conservative.

Kinetics

For this investigation it will be assumed that the rate of oxidation of BVS is a function only of BVS concentration and temperature and is first order with respect to BVS concentration as shown below:

$$\frac{d(BVS)}{dt} = -K_T\,(BVS) \qquad (12)$$

where:

(BVS) = concentration of biodegradable volatile solids, lb/cu ft.

K_T = reaction rate coefficient, $days^{-1}$, at temperature T (°C).

t = time, days.

A plot of this equation for an assumed K_T of 0.1 $days^{-1}$ at 20°C and a F_{BVS} of 0.7 is presented in Figure 2. Values of K_T at different temperatures which have been estimated from the literature are given in Table V. The values given should be considered only as estimates since, as pointed out by Barnhart (20), they are influenced by the value selected for F_{BVS} as well as by many other factors. F_{BVS} should actually be calculated from the experimental data in a manner analogous to the calculation of first stage BOD. As previously discussed, it is expected that F_{BVS} would also be a function of temperature.

Undoubtedly, the true rate equation is more complex than the simple first order reaction which has been assumed. The complexity of the reactions involved is illustrated in Figure 1 and in addition to BVS concentration and temperature, the rate coefficient could also be influenced by such factors as:

1. Mixing.
2. Oxygen transfer rate.
3. Composition of organic solids.
4. Concentration of microorganisms.

TABLE IV

OXYGEN EQUIVALENTS CALCULATED FROM HEATS OF COMBUSTION

Fraction of Solids that are volatile F_{VS}	Fresh Sludge		Activated Sludge	
	$\frac{BTU^a}{lb\ VS}$	$\frac{(OE)_c\ lb\ O_2}{lb\ VS}$	$\frac{BTU^a}{lb\ VS}$	$\frac{(OE)_c\ lb\ O_2}{lb\ VS}$
0.80	12,500	1.96	10,800	1.68
0.70	11,900	1.86	10,300	1.60
0.60	11,300	1.76	9,800	1.52
0.50	10,700	1.67	9,200	1.42

[a]Fair and Moore (36)

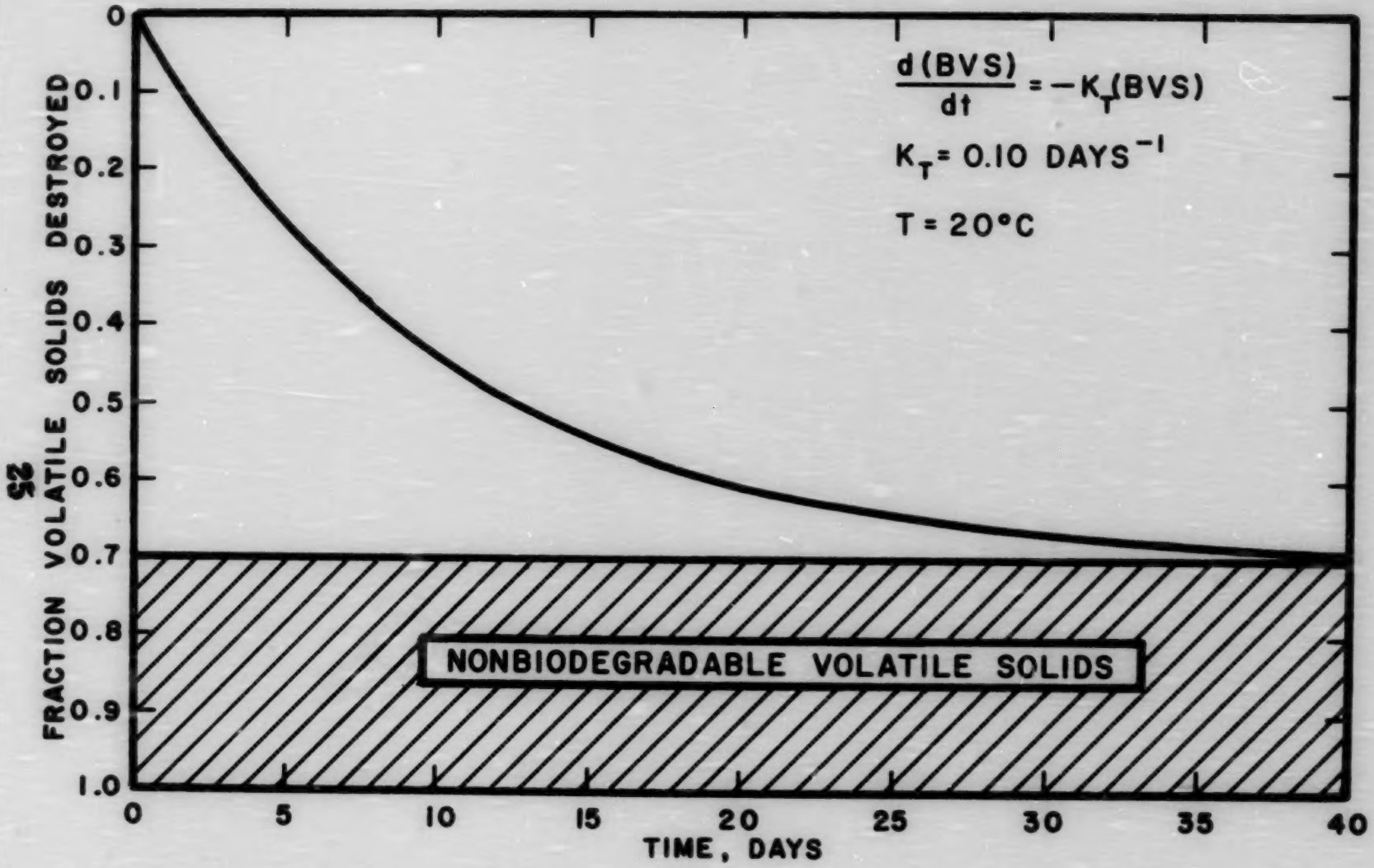

FIGURE 2. OXIDATION OF VOLATILE SOLIDS AS A FIRST ORDER REACTION

TABLE V

ESTIMATION OF FIRST ORDER REACTION RATE COEFFICIENT

Material	Estimated Rate Coefficient K_T, Days^{-1}	Temperature ^oC	Reference & Comments
Primary and waste activated sludge from domestic sewage	0.09 0.10 0.12	15 20 35	Jaworski, et al (19)[a] Reactor fed daily Assumed F_{BVS}= 0.7
Primary and waste activated sludge from domestic sewage	0.15 0.19 0.22	15 20 35	Jaworski, et al (19)[a] Reactor fed daily Assumed F_{BVS} = 0.5
Textile and domestic sewage	0.43	-	Barnhart (20) Feeding rate not reported F_{BVS}= 0.60
Pharmaceutical waste	0.46	-	Barnhart (20) Feeding rate not reported F_{BVS}= 0.75
Primary and waste activated sludge from domestic sewage	0.20	20	Lawton and Norman (21)[a] Reactor fed daily Assumed F_{BVS}= 0.6
Night soil	0.10 0.15 0.25	20 50 60	Reyes and Kruse (22) Batch reactor
Waste activated sludge from domestic sewage (Biosorption process)	0.53-0.85	-	Reynolds (23) Batch reactor F_{BVS} = 0.46-0.55
Thermophilic microorganisms	0.14 0.18 0.24 0.38 0.59	45 50 55 60 65	Kambhu (11)[a] Batch tests on organisms grown in continuous flow reactor Assumed F_{BVS}= 0.7

[a]Calculated from data given in reference listed.

5. Concentration of nutrients.

6. Inhibitors.

7. Species of microorganisms.

8. Physiological condition of microorganisms.

Kambhu (11) has developed a more fundamental rate equation for the growth on soluble substrates of mixed cultures of thermophilic microorganisms in which organism decay and the utilization of substrate for maintenance energy are considered. However, insufficient knowledge is available at present to construct a reaction rate function for the destruction of organic solids which will consider all of the important variables. Even if such a function could be developed, it is unlikely that it would be applied to design or operation because of its complexity. The use of first order kinetics has a long history in sanitary engineering and, as a first approximation, appears justified for a new process such as thermophilic aerobic digestion.

Temperature and Kinetics. The kinetics of microbial reactions are greatly influenced by temperature and reviews of the effects of temperature on microbial kinetics have been presented by Ingraham (37), Farrell and Rose (38), and Morgan and Edwards (39), among others. Temperature affects all of the reactions portrayed in Figure 1 and there may be different temperature optima for each reaction as illustrated by Senez (16) who reports that the maximum respiratory activity of Aerobacter aerogenes occurs at 41.8° C while the maximum rate of synthesis is at 37° C.

The Arrhenius equation has frequently been used to quantitatively express the relationship between the reaction rate coefficient and temperature. Over a limited range of temperature, this is often approxi-

mated by the simplified equation given below:

$$K_T = K_{TR} C^{(T - T_R)} \quad (13)$$

where:

K_{TR} = reaction rate coefficient, days^{-1}, at some reference temperature, T_R (°C).

C = temperature coefficient.

Temperature coefficients for the biological processes used in wastewater treatment have been found to range from 1.03 to 1.07. Still another way of expressing the effects of temperature on reaction rate is by the term Q_{10} or the number of fold increase in the rate of a process for each 10° C rise in temperature. A "rule of thumb" value commonly used is that Q_{10} is equal to 2.0 which corresponds to a value for C in Equation 13 of 1.072.

As temperature continues to increase, an optimum will be reached and, for pure cultures, the rate falls off very rapidly after the optimum. Ingraham (37) has presented a relatively fundamental equation to express this effect and Morgan and Edwards (39) have used this expression for simululating the effects of temperature on microbial cell propagators. However, for the purposes of this report, a simplified equation which uses terms more familiar in the wastewater treatment field has been adopted. This may be expressed as:

$$K_T = K_{TR1} \left[C_1^{(T - T_{R1})} - C_2^{(T - T_{R2})} \right] \quad (14)$$

where:

K_{TR1} = reaction rate coefficient, days^{-1}, at temperature T_{R1}.

C_1, C_2 = temperature coefficients.

T_{R1}, T_{R2} = reference temperatures, °C.

A plot of Equation 14 for K_{TR1} of 0.1 $days^{-1}$ at T_{R1} = 20° C and appropriate values for the other parameters is given in Figure 3. Accurate values are not available for these parameters; however, the numbers chosen should be reasonable and can serve to illustrate the effects of temperature on the process. It will be noted that the values of K_T presented in Figure 3 range from 0.1 $days^{-1}$ at 20° C to a maximum of 0.3 $days^{-1}$ at 57° C and decreases to zero at 68° C. These values for K_T appear reasonable when compared with those given in Table V. Tanner and Wallace (40) and Hansen (41) have found that the optimum temperature for many thermophils is about 55° C. Heukelekian (42) has shown that the maximum rate of anaerobic digestion occurs at 55° C with the rate being only slightly less at 50 and 60° C. Although a few species of microorganisms can grow at temperatures as high as 90° C (43), the maximum temperature for growth in this study has been set conservatively at 68° C.

For process design and operation, it may well be that Equation 13 (with appropriate temperature limits) instead of Equation 14 should be used to reduce the complexity of the model. However, for planned studies on the dynamics of the process it was desirable to have a continuous and more realistic function such as that shown in Figure 3.

STEADY STATE MATHEMATICAL MODEL

A mathematical model for a particular type of reactor can be developed by applying material and energy balances using the basic stoichiometric, thermochemical, and kinetic relationships for the major reactions involved. Many types of reactors, such as plug flow, complete-mixing, recycle, reactors in series, etc., are available. The model developed may be steady state (time independent) or dynamic (time depen-

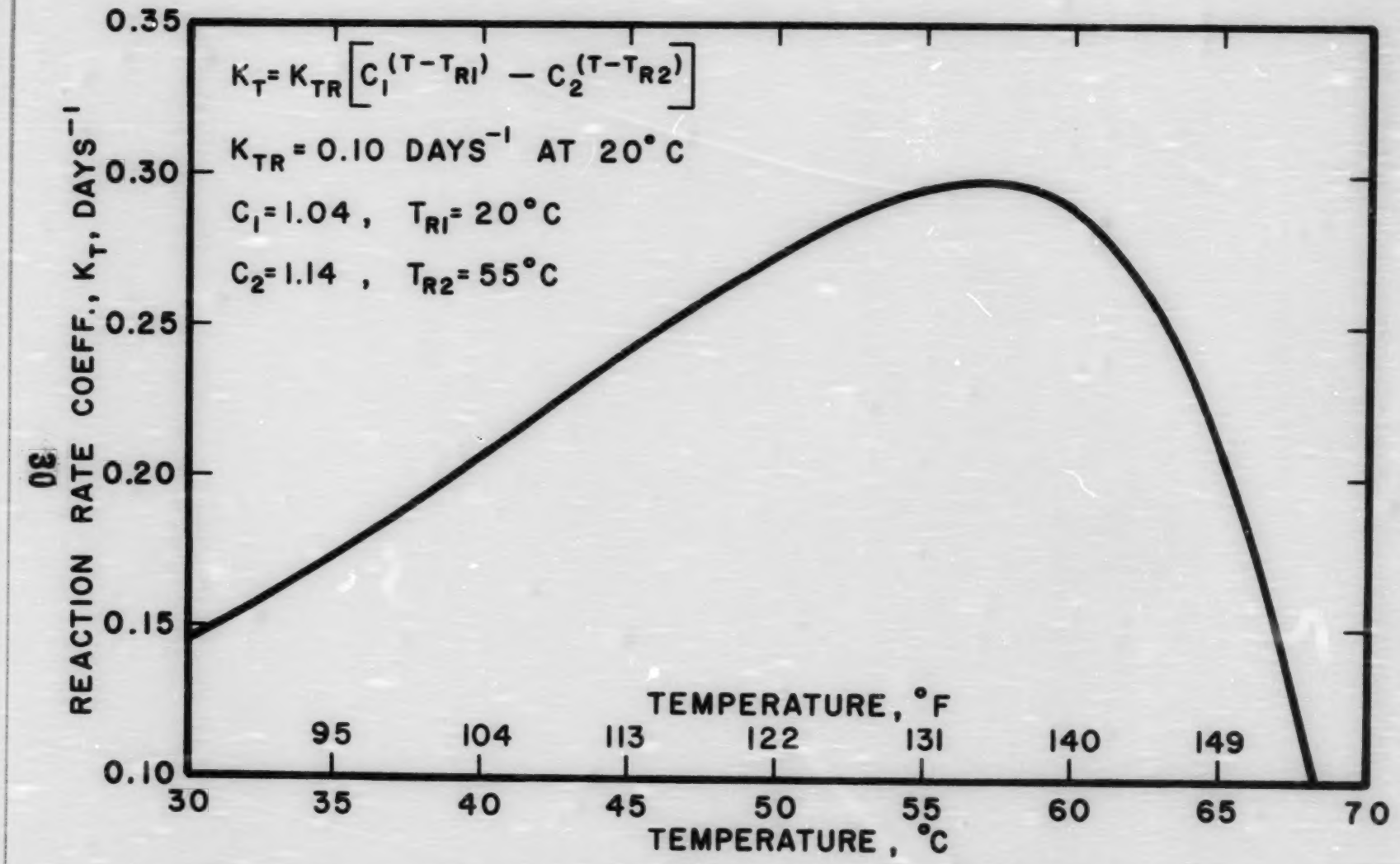

FIGURE 3. K_T AS A FUNCTION OF TEMPERATURE

dent). Thermophilic aerobic digestion is a new process and for this reason a simple reactor system, a complete-mixing, continuous-flow reactor without recycle and at steady state, was selected for study. The inputs, outputs, and reactions for the reactor are illustrated in Figure 4. The growth of microorganisms in this type of reactor is called continuous culture in the microbiological literature. The theory of continuous culture was first developed by Novic and Szilard (44) and Monod (45) in 1950 and since that time a sizeable body of literature and several major symposia (46, 47, 48, 49, 50) have been devoted to the subject with the most extensive reference work to date being that edited by Malek and Fencl (51).

A material balance is nothing more than an application of the principle of conservation and can be applied to any component in the reactor. The general form for a material or energy balance is as follows:

$$\begin{bmatrix}\text{Rate of}\\ \text{Accumulation}\\ \text{in Reactor}\end{bmatrix} = \begin{bmatrix}\text{Rate of}\\ \text{Flow Into}\\ \text{Reactor}\end{bmatrix} - \begin{bmatrix}\text{Rate of}\\ \text{Flow Out of}\\ \text{Reactor}\end{bmatrix} \pm \begin{bmatrix}\text{Rate of}\\ \text{Appearance or}\\ \text{Disappearance}\\ \text{due to Reaction}\end{bmatrix} \quad (15)$$

Each of the terms presented in the general equation may have more than one component, i.e., there may be several streams containing the material of interest which enter or leave the reactor and the material may be involved in more than one reaction. For a steady state balance the rate of accumulation term is zero which simplifies the equation by reducing the differential equation to an algebraic equation which is easily solved. For a non-steady state or dynamic balance, the rate of accumulation term is not zero and the use of the computer is usually necessary to obtain solutions.

Biodegradable Volatile Solids Balance

The material balance for the BVS in a complete-mixing, continuous-

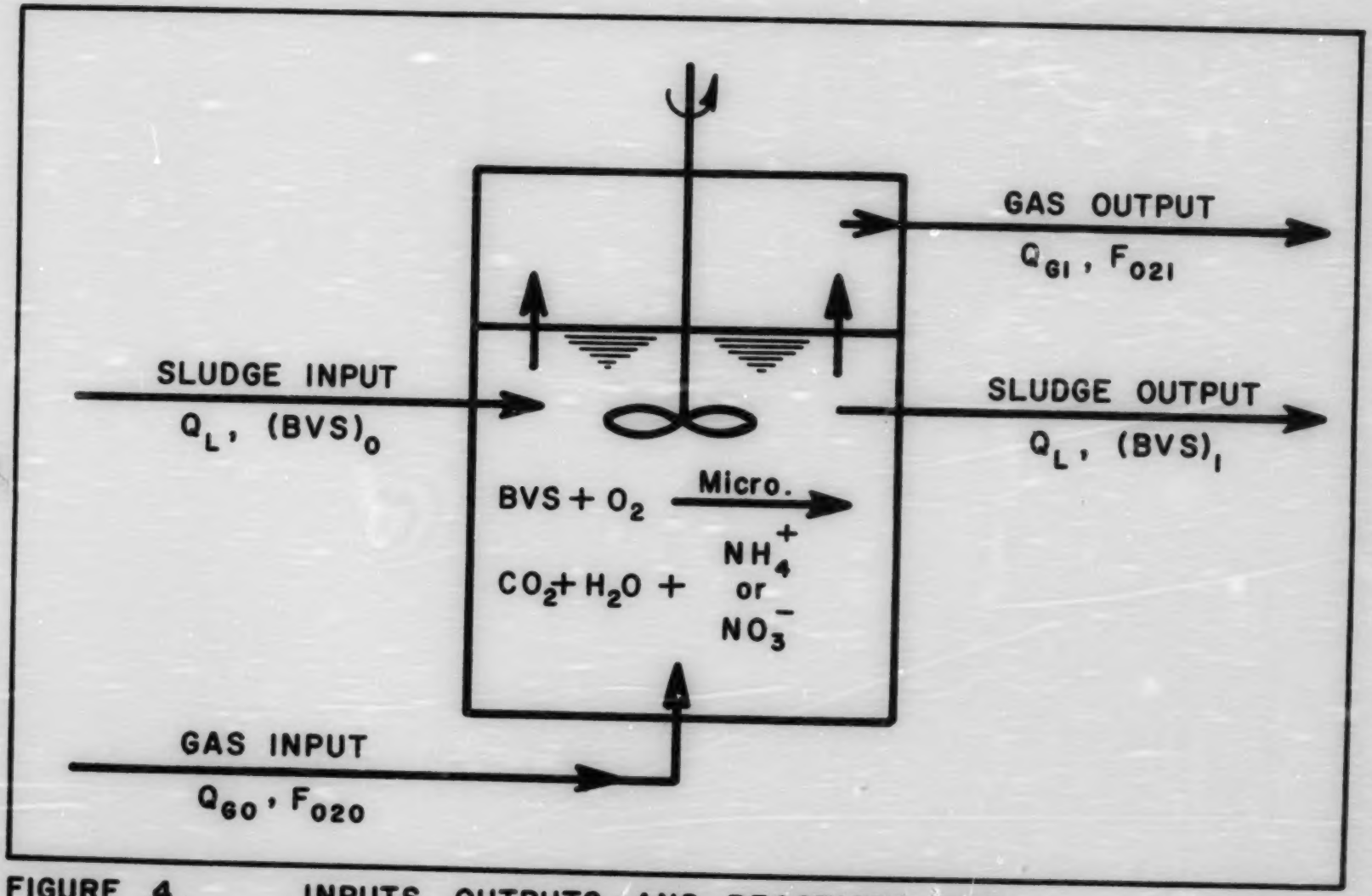

FIGURE 4. INPUTS, OUTPUTS, AND REACTIONS FOR THERMOPHILIC AEROBIC DIGESTER

flow reactor is as follows:

$$\begin{bmatrix}\text{Rate of Accumulation of BVS in Reactor}\end{bmatrix} = \begin{bmatrix}\text{BVS Input Rate}\end{bmatrix} - \begin{bmatrix}\text{BVS Output Rate}\end{bmatrix} - \begin{bmatrix}\text{Rate of BVS Oxidized}\end{bmatrix} \qquad (16)$$

$$V\frac{d(BVS)_1}{dt} = Q_L (BVS)_o - Q_L (BVS)_1 - K_T (BVS)_1 V \qquad (17)$$

where:

(BVS) = concentration of biodegradable volatile solids, lb/cu ft.

V = reactor volume, cu ft.

Q_L = sludge flow rate to reactor, cu ft/day

o = subscript denoting influent

1 = subscript denoting effluent

Equation 16 can be reduced from a differential equation to an algebraic equation by setting the first term equal to zero. Dividing through by V also permits expression in terms of reactor residence time.

$$0 = \frac{(BVS)_o}{\theta} - \frac{(BVS)_1}{\theta} - K_T (BVS)_1 \qquad (18)$$

where:

θ = reactor residence time, days

The concentration of BVS in the reactor effluent is:

$$(BVS)_1 = \frac{(BVS)_o}{(1 + K_T\theta)} \qquad (19)$$

From the section on stoichiometry it will be noted that $(BVS)_o$ can be replaced by $(F_{BVS})(VS)_o$ or $(F_{BVS})(F_{VS})(TS)_o$ where:

F_{BVS} = fraction of volatile solids that are biodegradable.

F_{VS} = fraction of total solids that are volatile.

$(VS)_o$ = concentration of volatile solids in influent, lb/cu ft.

$(TS)_o$ = concentration of total solids in influent, lb/cu ft.

The fraction of volatile solids that are destroyed in the reactor may be calculated as:

$$F_{VSD} = \frac{(BVS)_o - (BVS)_1}{(VS)_o} \qquad (20)$$

where:

F_{VSD} = fraction of volatile solids destroyed, approaches F_{BVS} as a limit.

A plot of the interactions between residence time and reaction coefficient (and therefore temperature) is given in Figure 5. An increase in the reaction rate coefficient decreases the residence time requirements for a fixed destruction of volatile solids. For example, residence time requirements are 8, 12, and 25 days for K_T values of 0.3, 0.2, and 0.1 $days^{-1}$, respectively, to attain a 50 percent destruction of volatile solids. These residence times could be decreased by intermittent operation in which the solids are allowed to settle and the supernatent decanted; however, this has not been considered in the model.

Oxygen Balance

A steady state oxygen balance can be derived in a manner similar to the BVS balance as shown below:

$$0 = \left[\begin{matrix}O_2 \text{ Input} \\ \text{Rate}\end{matrix}\right] - \left[\begin{matrix}O_2 \text{ Output} \\ \text{Rate}\end{matrix}\right] - \left[\begin{matrix}\text{Rate of} \\ O_2 \text{ Utilization} \\ \text{for BVS} \\ \text{Oxidation}\end{matrix}\right] \qquad (21)$$

The rate at which oxygen is utilized for BVS oxidat[illegible] be determined from the rate of BVS oxidation in the reactor as given in Equation 17 and the oxygen equivalent of the BVS. In calculating the

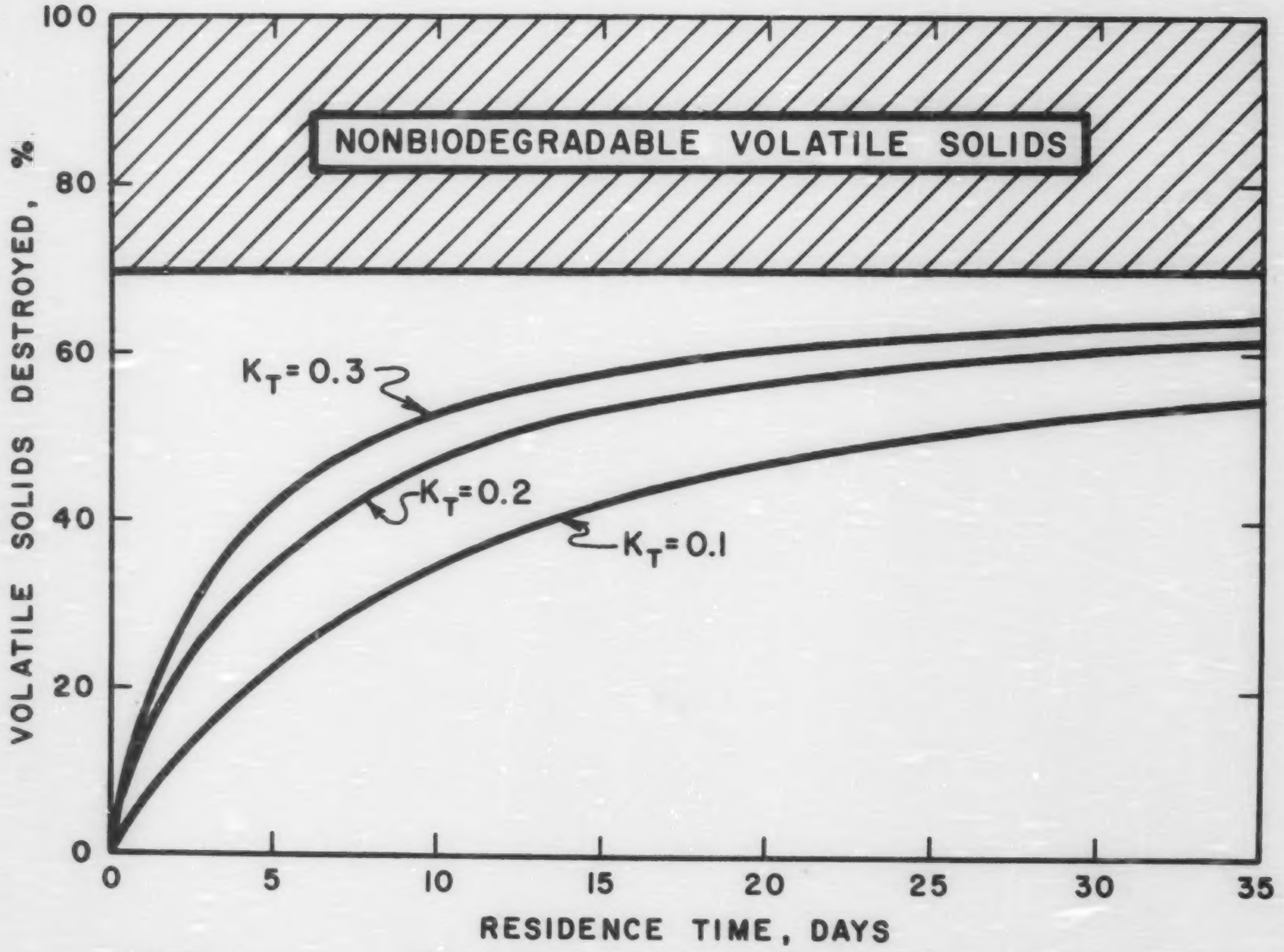

FIGURE 5. RESIDENCE TIME – REACTION RATE COEFFICIENT INTERACTIONS

rate of oxygen utilization, it is necessary to consider whether the nitrogen in the BVS is converted to ammonia or nitrate. For ammonia as a product:

$$(R)_{02U} = (OE)_C \, K_T \, (BVS)_1 \, V \tag{22}$$

whereas for nitrate as a product:

$$(R)_{02U} = [(OE)_C + 4.56 \, F_N] \, K_T \, (BVS)_1 \, V \tag{23}$$

where:

$(R)_{02U}$ = rate of oxygen utilization in reactor, lb/day

$(OE)_C$ = oxygen equivalent of BVS for ammonia as product, lb O_2/lb BVS.

F_N = fraction of nitrogen in the BVS.

The oxygen inputs and outputs must be expressed in terms of the gas flow rates into and out of the reactor for later use in the heat balance. The quantity of oxygen leaving the reactor in the liquid as dissolved oxygen is small and can be neglected. For a given oxygen transfer efficiency, the required influent gas flow rate may be calculated as:

$$Q_{GO} = \frac{(R)_{02U}}{F_{02O} D_{02} F_{TEF}} \tag{24}$$

where:

Q_{GO} = influent dry gas flow rate at STP (1 atm, 60° F), cu ft/day.

D_{02} = density of dry oxygen, lb/cu ft, equals 0.0843 at STP.

F_{02O} = fraction of oxygen (by volume) in the influent gas, equals 0.21 for air.

F_{TEF} = oxygen transfer efficiency or fraction of influent oxygen utilized in the oxidation of BVS.

As previously discussed, the volumetric flow rates of dry gas into

and out of the reactor will be approximately equal when the nitrogen in the BVS is oxidized to ammonia and Q_{GO} therefore approximately equals Q_{GI} where Q_{GI} is the effluent dry gas flow rate. However, this will not be the case when the nitrogen is converted to nitrate. For nitrate as a product, the influent dry gas flow rate should be calculated by substituting the value of $(R)_{O2U}$ obtained from Equation 23 into Equation 24 whereas the effluent dry gas flow rate should be calculated by using the value of $(R)_{O2U}$ obtained from Equation 22.

Since some of the oxygen will be replaced by carbon dioxide in the passage of the gas through the reactor, the density of the effluent dry gas will be higher than that of the influent and may be calculated as:

$$D_{GI} = D_{GO} + F_{O2O} F_{TEF} (D_{CO2} - D_{O2}) \quad (25)$$

where:

D_{GI} = density of dry effluent gas, lb/cu ft.

D_{GO} = density of dry influent gas, lb/cu ft.

D_{CO2} = density of dry carbon dioxide, lb/cu ft, equals 0.107 at STP.

The mass flow rate of dry gas out of the reactor is needed for the heat balance and may now be calculated as $(D_{GI})(Q_{GI})$ where the products of nitrogen oxidation are taken into account in calculating Q_{GI}. It should be noted that for low oxygen transfer efficiencies, especially when air is used as the influent gas, little error would be introduced by assuming the dry densities of the influent and effluent gases to be equal.

The mass flow rate of water vapor in the effluent gas is also needed for the heat balance since the latent heat required to vaporize the water represents one of the most significant heat losses at thermophilic temperatures. The partial pressure of water vapor at different

temperatures can be found in handbooks (30) but may also be approximated from expressions such as that given in Equation 26.

$$\text{Log } P_{H2O} = (a)\frac{1}{T_A} + b \qquad (26)$$

For P_{H2O} in millimeters of mercury and the temperature, T_A, in degrees Kelvin, a and b are -2238 and 8.896, respectively. The absolute humidty, A_H, may now be calculated as:

$$A_H = \left[\frac{D_{H2O}}{D_{GI}}\right] \left[\frac{P_{H2O}}{(P_T - P_{H2O})}\right] \qquad (27)$$

where:

A_H = absolute humidity, lb H_2O vapor/lb dry air.

D_{H2O} = density of water vapor, lb/cu ft, equals 0.053 at STP.

P_{H2O} = partial pressure of water vapor, mm Hg.

P_T = total pressure of wet gas in effluent, mm Hg, assumed to be constant at atmospheric or 760 mm Hg.

The mass flow rate of water vapor in the effluent gas can now be calculated as (A_H) (D_{GI}) (Q_{GI}). It will be conservative to assume that the influent gas is dry and the effluent gas is saturated with water vapor.

Heat Balance

The heat balance, as shown below, is expressed in the same general manner as the BVS and oxygen balances; however, the output or heat losses

$$0 = \begin{bmatrix}\text{Heat}\\ \text{Input}\\ \text{Rate}\end{bmatrix} - \begin{bmatrix}\text{Heat}\\ \text{Output}\\ \text{Rate}\end{bmatrix} + \begin{bmatrix}\text{Rate of Heat}\\ \text{Production}\\ \text{from BVS}\\ \text{Oxidation}\end{bmatrix} \qquad (28)$$

consist of several terms which will be discussed separately. A schematic of the reactor showing the terms considered in the heat balance is pre-

sented in Figure 6.

Heat Input from Mixing. The power input for mixing, whether it be from compression of the influent gas or mechanical stirring, results in an input of heat to the reactor. This heat input can be estimated from the horsepower input per unit volume of reactor, the volume of the reactor, the BTU equivalent of the horsepower (61,100 BTU/HP-Day), and is equal to:

$$H_M = 61{,}100\ (HP)_V\ V \qquad (29)$$

where:

H_M = rate of heat input from mixing and gas supply, BTU/day.

$(HP)_V$ = horsepower input per unit volume of reactor, HP/cu ft.

Both oxygen transfer efficiencies and reaction rates are influenced by power input; however, these are complex interactions and were not the subject of this investigation. Walker and Drier (52) have indicated that the required power input for conventional aerobic digestion is primarily determined by mixing requirements and is approximately 1.0 HP per 1000 cu ft of reactor. This power requirement could likely be reduced by using turbine aeration as frequently practiced in the activated sludge process.

Biological Heat Production. The heat produced in the biological oxidation of the BVS can be calculated from the oxygen uptake rate considering whether the nitrogen in the BVS is converted to ammonia or to nitrate. For ammonia as a product, 6,100 BTU of heat is generated for each lb of oxygen utilized and the heat production rate is:

$$H_B = 6{,}100\ (R)_{O2U} \qquad (30)$$

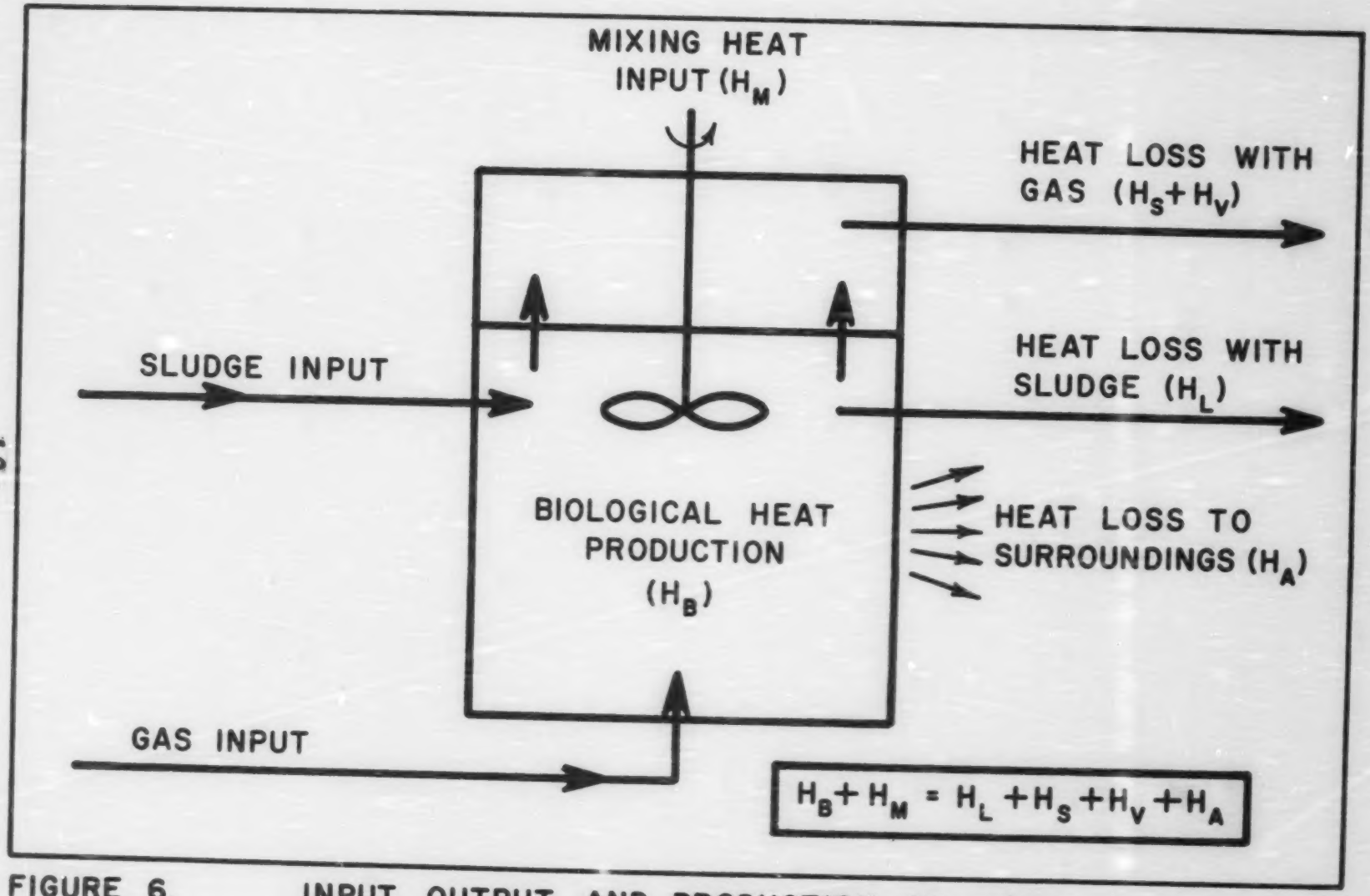

FIGURE 6. INPUT, OUTPUT, AND PRODUCTION OF HEAT FOR THERMOPHILIC AEROBIC DIGESTER

For nitrate as a product, the heat production rate is equal to:

$$H_B = 6{,}100\ (R)_{O2U} + 11{,}000\ F_N\ K_T\ (BVS)_1\ V \qquad (31)$$

where:

H_B = rate of heat production by biological oxidation of BVS, BTU/day.

The rate of oxygen utilization for use in both Equations 30 and 31 should be that calculated from Equation 22 which does not include the oxygen required to convert ammonia to nitrate.

Heat Loss in Effluent Sludge. The temperature of the effluent sludge is the same as that of the sludge in the reactor and the heat loss is therefore equal to the amount of heat required to raise the temperature of the influent sludge to the operating temperature of the reactor. This is one of the largest of the heat losses and may be expressed as:

$$H_L = D_L\ C_{PL}\ Q_L\ (T_{L1} - T_{L0}) \qquad (32)$$

where:

H_L = rate of net heat loss in effluent sludge, BTU/day.

D_L = density of sludge, lb/cu ft.

C_{PL} = specific heat of sludge, BTU/lb/°F.

T_{L0} = temperature of influent sludge, °F.

T_{L1} = temperature of effluent sludge, °F.

D_L and C_{PL} are relatively constant over the thermophilic range of temperatures and are assumed equal to 63.0 lb/cu ft and 1.0 BTU/lb/°F, respectively.

Heat Loss as Latent Heat in Water Vapor. The latent heat required to vaporize the water contained in the effluent gas represents one of the most significant heat losses at thermophilic temperatures. Little

error is introduced by assuming the heat of vaporization to be constant at 1,020 BTU/lb of water vapor over the thermophilic temperature range and the heat loss is therefore equal to this number times the mass flow rate of the water vapor as given below:

$$H_V = 1{,}020\ A_H\ D_{G1}\ Q_{G1} \tag{33}$$

where:

H_V = rate of heat loss as latent heat in water vapor, BTU/day.

The assumption is made that the influent gas is dry and the effluent gas is saturated with water vapor. The absolute humidity, A_H, for use in calculating the mass flow rate of the water vapor, is determined from Equations 26 and 27. Since A_H is an exponential function of temperature, the latent heat loss can exceed the heat loss in the effluent sludge at higher temperatures and can limit the maximum temperature attainable in the reactor.

Heat Loss as Sensible Heat in Effluent Gas. Little error is involved in the overall heat balance by assuming that the specific heats and mass flow rates of the influent and effluent dry gases are equal for sensible heat loss calculations. The temperature of the effluent gas is also assumed to be equal to the effluent sludge temperature. With these assumptions, the net sensible heat loss can be calculated as:

$$H_S = [D_{G1}\ C_{PG1}\ Q_{G1} + A_H\ C_{PH2O}\ D_{G1}\ Q_{G1}]\ [T_{G1} - T_{GO}] \tag{34}$$

where:

H_S = rate of net sensible heat loss in effluent gas, BTU/day.

C_{PG1} = specific heat of dry effluent gas, BTU/lb/°F.

C_{PH2O} = specific heat of water vapor, BTU/lb/°F.

T_{G1} = temperature of effluent gas, °F, and is assumed equal to the temperature of the effluent sludge, T_{L1}.

T_{GO} = temperature of influent gas, °F, and is assumed equal to air temperature outside the reactor.

C_{PG1} and C_{PH2O} are relatively constant over the thermophilic range of temperatures and are assumed equal to 0.24 and 0.45 BTU/lb/°F, respectively.

Heat Loss to Surroundings. The heat lost to the surroundings through the surface area of the reactor can be calculated using the conventional heat transfer equation which is:

$$H_A = 24\ U\ A\ (T_{L1} - T_{GO}) \tag{35}$$

where:

H_A = rate of heat loss to surroundings, BTU/day.

U = overall heat transfer coefficient, BTU/sq ft/hr/°F.

A = surface area of reactor, sq ft.

As previously mentioned, T_{L1} is the temperature of the sludge in the reactor and T_{GO} is the temperature of the air outside the reactor as well as the temperature of the influent gas.

Summary

At steady state the overall heat balance may now be expressed as shown below with the terms indicated being defined more specifically in Equations

$$H_M + H_B = H_L + H_V + H_S + H_A \tag{36}$$

29, 30 or 31, 32, 33, 34, and 35. It should again be noted that H_B may have either of two values depending upon whether the nitrogen in the volatile solids is converted to ammonia or nitrate.

A summary of the mathematical model showing the information flow needed to calculate the significant variables is given in Figure 7. It will be noted that an iterative or "trial and error" technique is required for solution of the equations and this is most easily accomplished by using the digital computer.

SIMULATION STUDIES

The studies presented herein should be considered only semiquantitative in nature since it has been necessary to make several simplifying assumptions in developing the model and reliable values for many of the parameters are not available. Especially needed are more data concerning the effects of temperature on F_{BVS} and K_T. Also, the assumption of first order kinetics may not be valid at high conversions of volatile solids since the compounds remaining at long residence times may be more resistant to biological degradation. However, even with these deficiencies simulation studies are of value in evaluating the effect of important design and operating variables on the process and in developing guidelines for pilot plant studies.

In order to make the simulations more meaningful, they are based on domestic wastewater sludge or mixtures of domestic wastewater sludge and ground garbage from a city with a population of 10,000. 70 percent of the total solids are assumed to be volatile and of the volatile solids, 70 percent are assumed to be biodegradable. The density of the influent sludge is assumed constant at 63.0 lb/cu ft. 1.5 lbs of oxygen is utilized for each lb of volatile solids destroyed and 6,100 BTU of heat is produced per lb of oxygen utilized (ammonia as a product). The power input for mixing and gas transfer is assumed constant at 1.0 HP per 1,000 cu ft of reactor. The simulated reactor is assumed cylin-

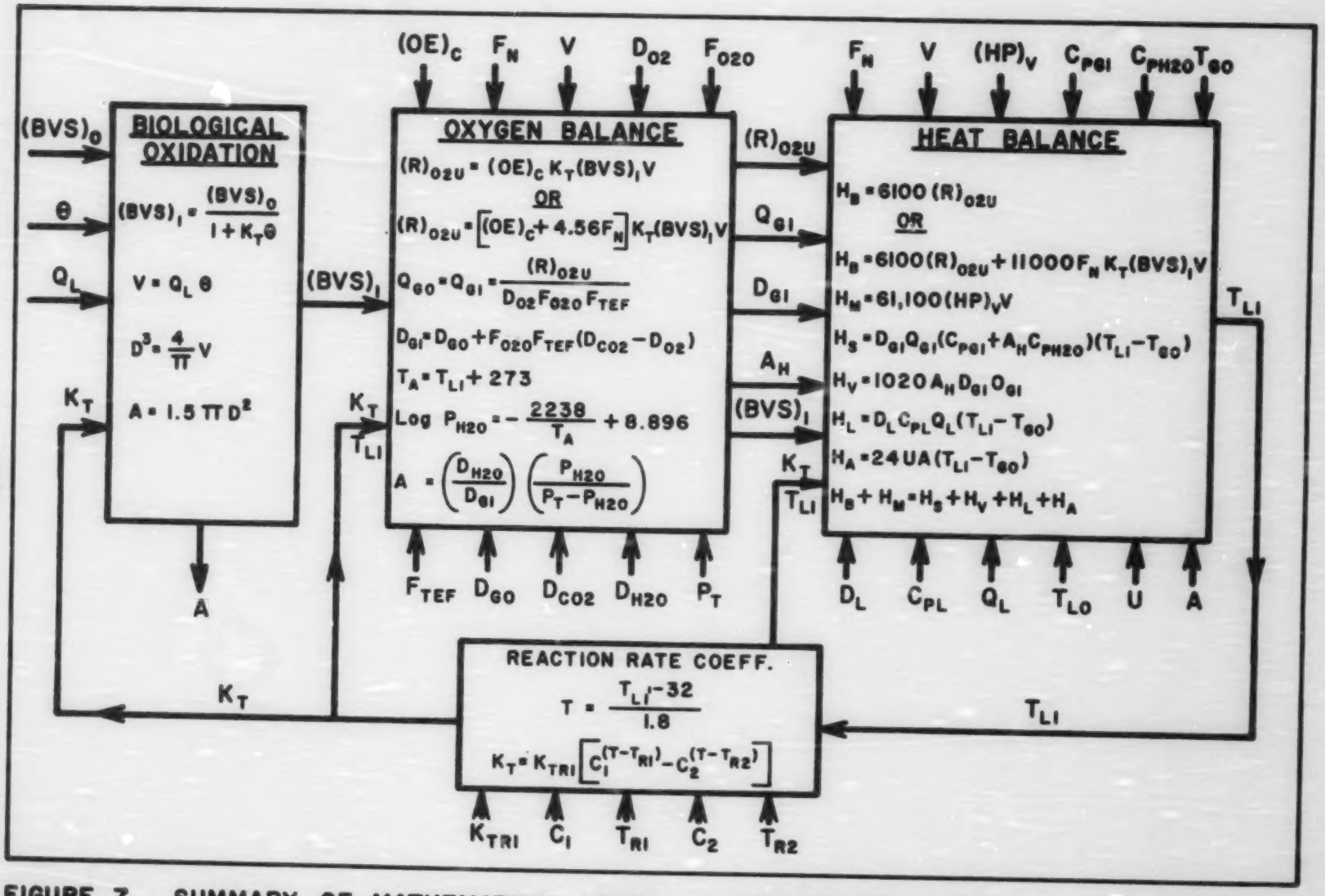

FIGURE 7. SUMMARY OF MATHEMATICAL MODEL & INFORMATION FLOW

drical with a height equal to the diameter. The input gas is dry and the effluent gas is saturated with water vapor. Since low temperatures will be critical for the process, an outside air temperature of 20° F and an influent sludge temperature of 40° F are assumed. A summary of these plus other assumed parameters for the simulations is presented in Table VI.

Simulations are presented for both isothermal and autothermal operation and for both air and oxygen as the influent gas. The conversion of organic nitrogen to either ammonia or nitrate is considered. The effects on the process of varying the residence time, total solids concentration, contribution of solids per capita, oxygen transfer efficiency, and the heat transfer coefficient are also given.

Isothermal Operation

Although it is not proposed that the process be operated under isothermal conditions, it is of interest to examine the terms in the heat balance (Eq. 36) to determine their relative significance. Figure 8 shows heat production and losses plotted vs. temperature for a contribution of 0.2 lb of total solids per capita per day (PCPD), residence time of 10 days, total solids concentration of 3 percent (w/w) in the influent sludge, oxygen transfer efficiency of 0.15, and an overall heat transfer coefficient of 0.10 BTU/sq ft/°F/hr. The volumetric flow rate into the reactor is 1,058 cu ft/day and the mass flow rate of volatile solids is 1,400 lb/day. The influent gas is air and organic nitrogen is converted to ammonia. The temperature at which the process would operate autothermally, 102° F, is located at the intersection of the total heat production and total heat losses curves and represents an increase in sludge temperature of (102 - 40) or 62° F. Excess

TABLE VI

ASSUMED PARAMETERS FOR SIMULATION OF THE THERMOPHILIC AEROBIC DIGESTION PROCESS

Parameter	Numerical Values and Units
C_1	1.04
C_2	1.14
C_{PL}	1.0 BTU/lb/^{o}F
C_{PGL}	0.24 BTU/lb/^{o}F for dry air
C_{PH2O}	0.45 BTU/lb/^{o}F for water vapor
D_L	63.0 lb/cu ft
D_{GO}	0.0854 lb/cu ft of dry air at STP (1 atm, 60^{o}F)
D_{O2}	0.0843 lb/cu ft of dry O_2 at STP
D_{CO2}	0.1070 lb/cu ft of dry CO_2 at STP
D_{H2O}	0.053 lb/cu ft of water vapor at STP
F_{VS}	0.70
F_{BVS}	0.70
F_N	0.05
$(HP)_V$	0.001 HP/cu ft of reactor
K_{TR1}	0.10 days^{-1}
$(OE)_C$	1.5 lb O_2 utilized/lb VS oxidized
Population	10,000 people
P_T	760 mm Hg total pressure of effluent gas
T_{GO}	20^{o}F outside air temperature
T_{LO}	40^{o}F influent sludge temperature
T_{R1}	20^{o}C
T_{R2}	55^{o}C

heat would be produced below this temperature and heat would have to be added to operate the reactor above this temperature. The heat produced through power input for mixing and gas transfer is relatively small compared to the heat produced by biological action.

The individual heat loss terms in the heat balance are presented in Figure 9. The largest heat loss is that in the liquid effluent from the process and in larger plants it might be worthwhile to reclaim some of this heat through heat exchange with the influent sludge. The next largest loss of heat is the latent heat of water vapor carried out in the effluent gases. This loss could be reduced by using more efficient gas transfer devices thereby reducing the required air flow rate or by using high purity oxygen.

Figures 10 and 11 represent isothermal operation where the total solids per capita per day and solids concentration have been increased to 0.3 lb PCPD and 4.5 percent, respectively, so that the volumetric flow rate remains constant at 1,058 cu ft/day while the mass flow rate of volatile solids increases from 1,400 to 2,100 lb/day. This could be accomplished by the addition of ground garbage to the sewers or by a central garbage grinding station located at the wastewater treatment plant. The increased mass flow rate of volatile solids results in a higher temperature (115° F vs 102° F) in the reactor through increased biological heat production. Figure 11 also indicates that a considerably larger fraction of the total heat losses is now due to the latent heat of water vapor in the effluent gases and at temperatures above 130° F this would represent the largest of the heat losses. Since the latent heat increases exponentially with temperature, it can become the major factor limiting the temperature attained in autothermal operation. This clearly illustrates the need for using high efficiency

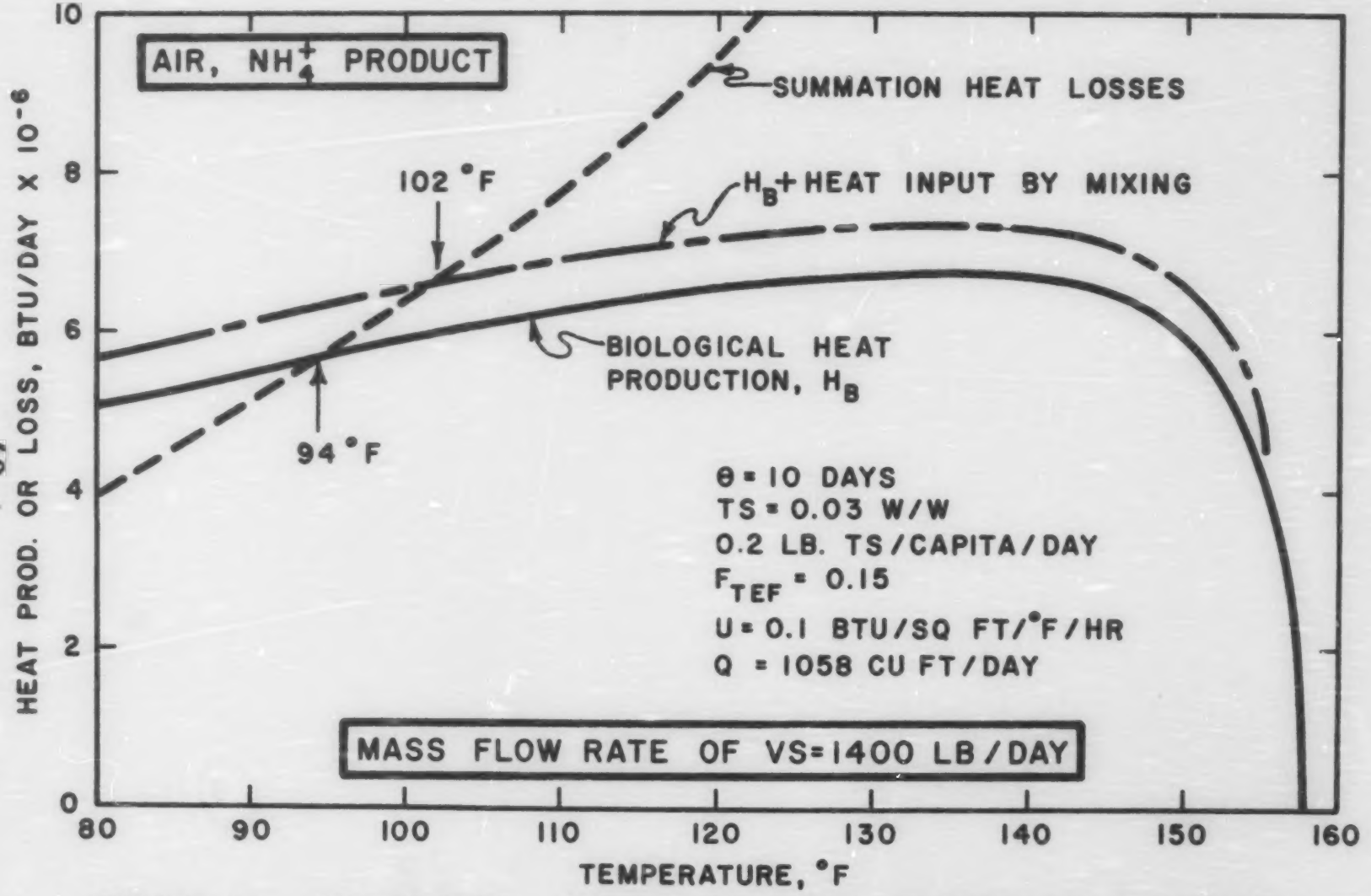

FIGURE 8. ISOTHERMAL OPERATION–HEAT PRODUCTION & LOSSES

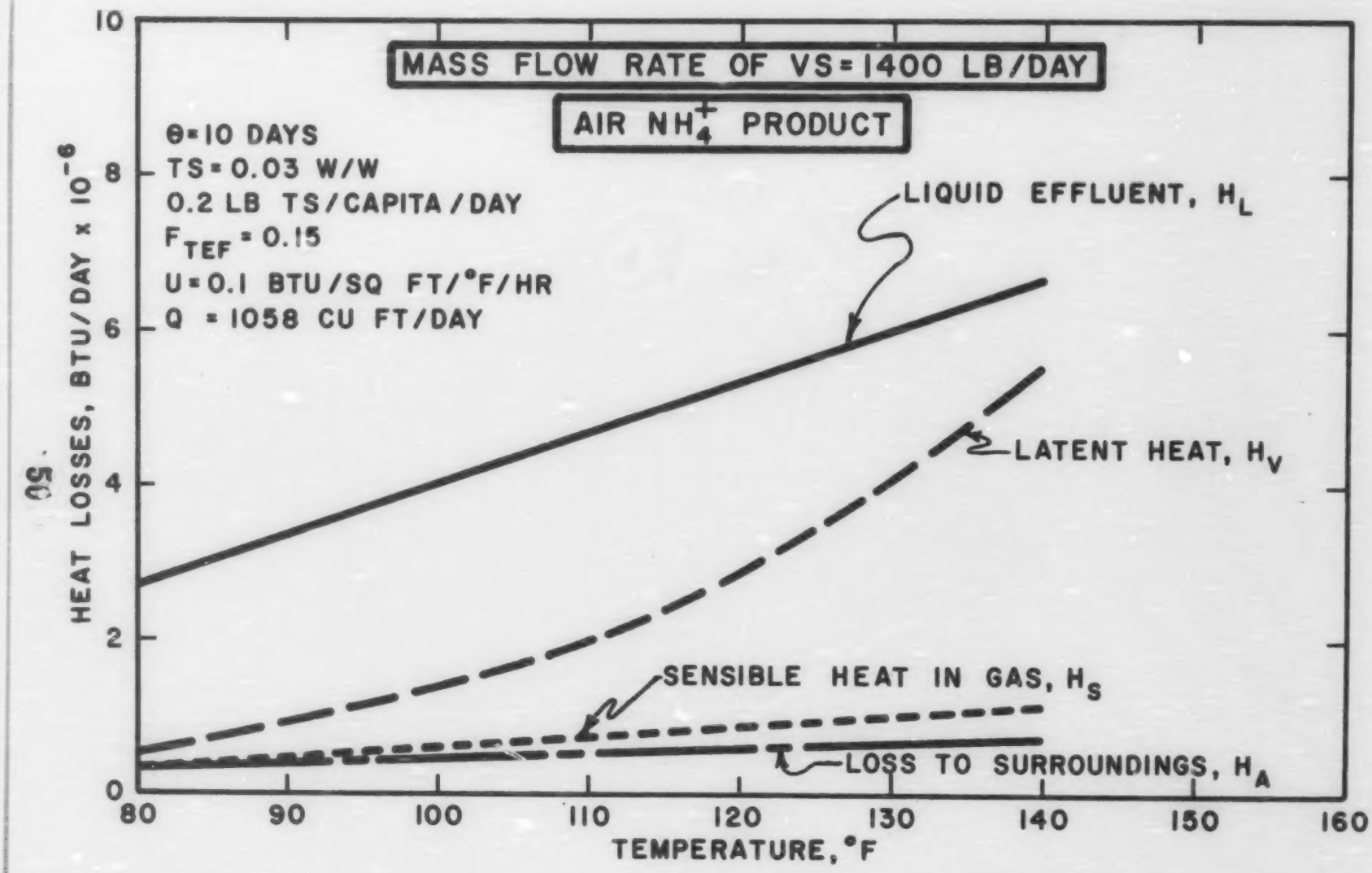

FIGURE 9. ISOTHERMAL OPERATION – HEAT LOSSES

gas transfer devices and the advantage of using high purity oxygen for the influent gas. The possibility also exists for reclaiming some of the latent heat through heat exchange with the influent sludge or gas.

Autothermal Operation

The previous figures indicate that sufficient heat can be generated through biological activity so that the process can be operated autothermally at temperatures considerably higher than ambient without a supply of external heat. The temperature at which the process will operate autothermally is located at the intersection of the total heat production and heat losses curves and may be determined by an iterative solution of Equation 36.

The results to be presented in this section should be compared with conventional design criteria for mesophilic aerobic digestion which call for a hydraulic residence time of 15 to 20 days and an air flow rate of 15 to 20 cfm/1000 cu ft of reactor (53). However, in making this comparison it should be remembered that conventional aerobic digesters are normally operated in an intermittent fashion in which mixing is stopped for a short period of time, the solids allowed to settle, the supernatent decanted, and mixing resumed. This results in solids residence times considerably higher than hydraulic residence times thus permitting a decrease in hydraulic residence time for a given percentage destruction of volatile solids. The model presented herein does not provide for this type of intermittent operation and the hydraulic residence times are therefore equal to the solids residence times. The operation of a thermophilic aerobic digester in an intermittent mode should result in decreased hydraulic residence times for the process. Another factor to keep in mind in comparing the two processes is that the simulations presented are for an outside air tem-

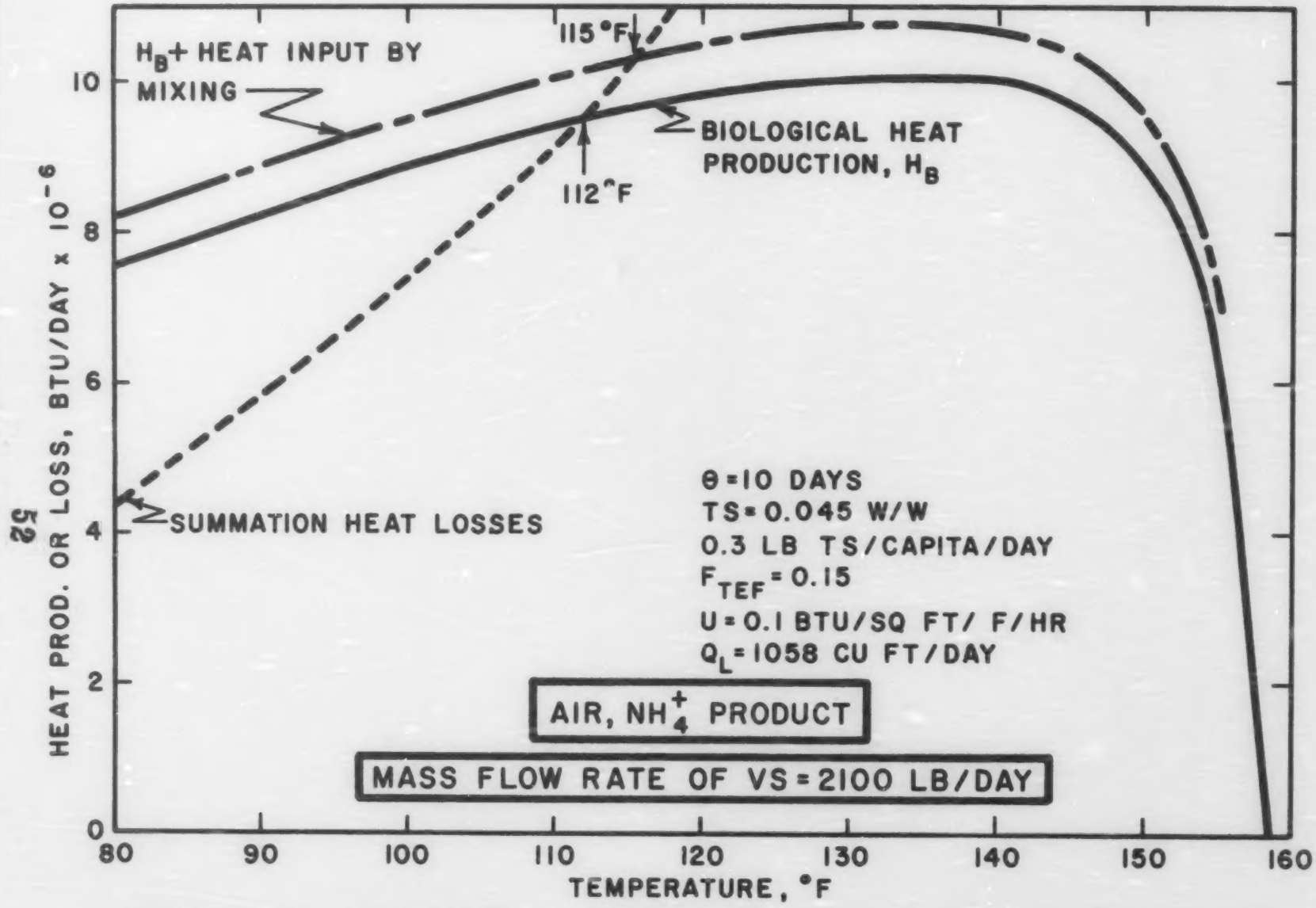

FIGURE 10. ISOTHERMAL OPERATION - HEAT PRODUCTION AND LOSSES

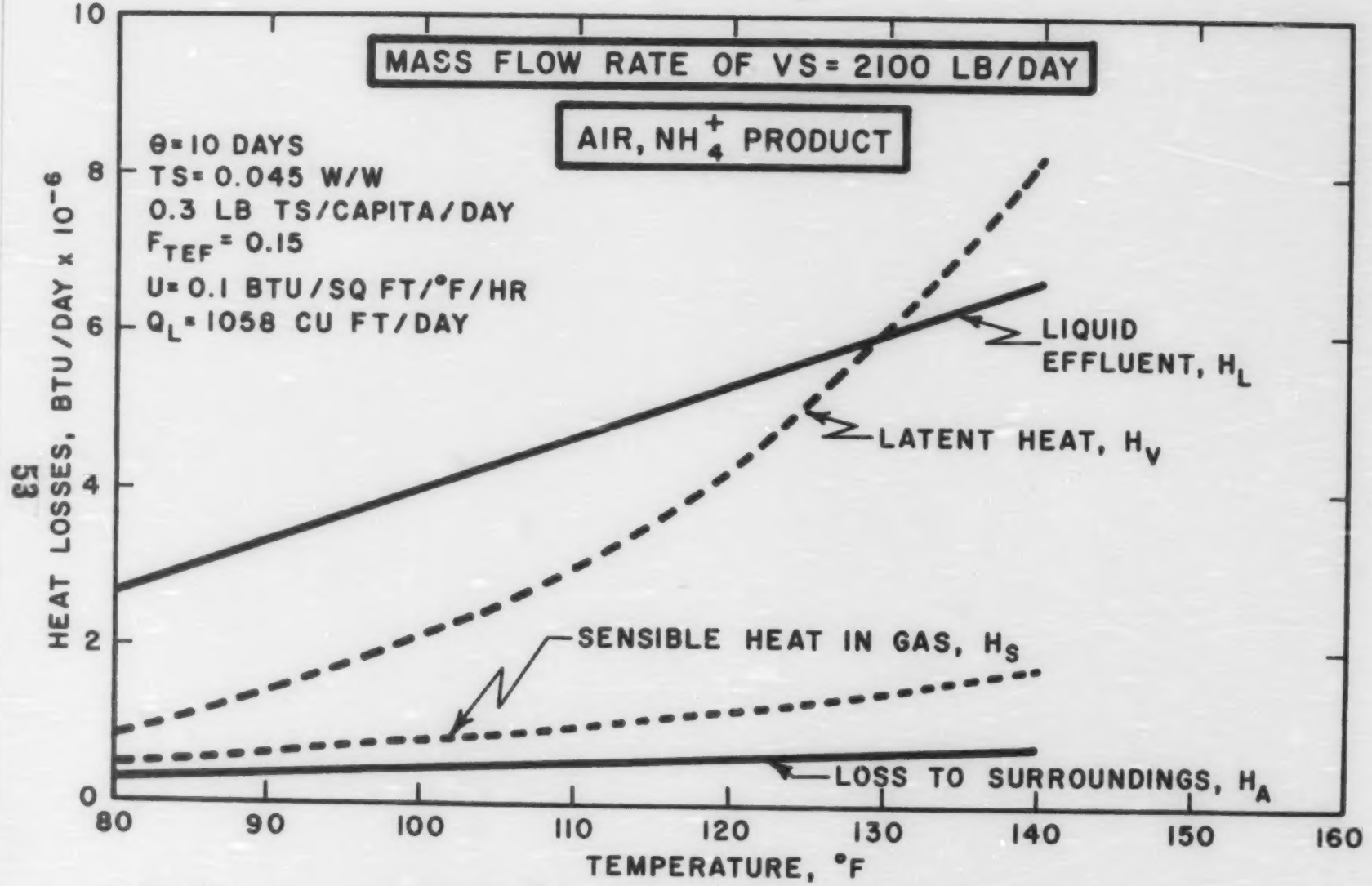

FIGURE 11. ISOTHERMAL OPERATION – HEAT LOSSES

perature of 20° F and an influent sludge temperature of 40° F which represent the more critical conditions for the process. Temperatures higher than these would prevail much of the time and would result in higher reactor temperatures with corresponding higher destruction of volatile solids.

Air as Influent Gas. The effect of residence time on the process is shown in Figure 12 for assumed values of 0.3 lb of total solids PCPD, a total solids concentration of 3.0 percent (w/w) in the influent sludge, oxygen transfer efficiency of 0.15, overall heat transfer coefficient of 0.1 BTU/sq ft/°F/hr, and ammonia as the product of organic nitrogen oxidation. Even with this relatively dilute sludge, reactor temperatures of 100° F (an elevation in sludge temperature of 60° F) are attained at all residence times greater than nine days and the percentage of volatile solids destroyed is greater than 40 percent for all residence times greater than 7.5 days. Although not shown, the influence of higher influent sludge and air temperatures would be to shift the curves to the left thus resulting in higher temperatures and higher percentages of volatile solids destroyed at lower residence times. As an example for influent sludge and air temperatures of 70° F, the reactor temperature and percentage of volatile solids destroyed at a residence time of six days are 116° F and 42 percent, respectively.

The reactor temperature is sensitive to oxygen transfer efficiency (and therefore air flow rate) as shown in Figure 13 where reactor temperature is plotted vs. oxygen transfer efficiency for a residence time of 10 days. This is as expected since one of the largest heat losses from the process is the latent heat of water vapor in the exit air stream. The increased air flow rates necessitated by low oxygen trans-

fer efficiencies result in a considerably higher mass flow rate of water vapor out of the reactor. The decreases in reactor temperature and percentage of volatile solids destroyed with decreasing oxygen transfer efficiency emphasize the importance of selecting an efficient aeration system for the process. Although not considered in the model, too low an aeration rate could also result in lower temperatures through an inability to meet the required oxygen uptake rate thus resulting in partially anaerobic conditions in the reactor. Heats of reaction are lower for anaerobic reactions than for aerobic reactions and odor problems could also result from anaerobic conditions.

Higher temperatures and increased volatile solids destruction can be attained by using thickening to increase the concentration of solids in the influent sludge. Figure 14 shows the effect of decreasing the volumetric flow rate to the reactor while holding the mass flow rate of volatile solids constant by thickening. The residence time is maintained constant at 10 days. The higher temperatures attained are primarily due to decreased heat losses in the liquid effluent because of the reduction in volumetric flow rate. Temperatures over 100° F are attained for all total solids concentrations greater than 2.8 percent and the percentage of volatile solids destroyed increases as the total solids in the influent increase.

Figure 15 illustrates the effect of increasing the mass flow rate of volatile solids to the reactor without increasing the influent sludge flow rate at a fixed residence time of 10 days. This could be accomplished by the use of garbage grinders with discharge to the sewerage system or by a central garbage grinding station located as the wastewater treatment plant. The higher temperatures are attained primarily because of the increased heat energy released from the des-

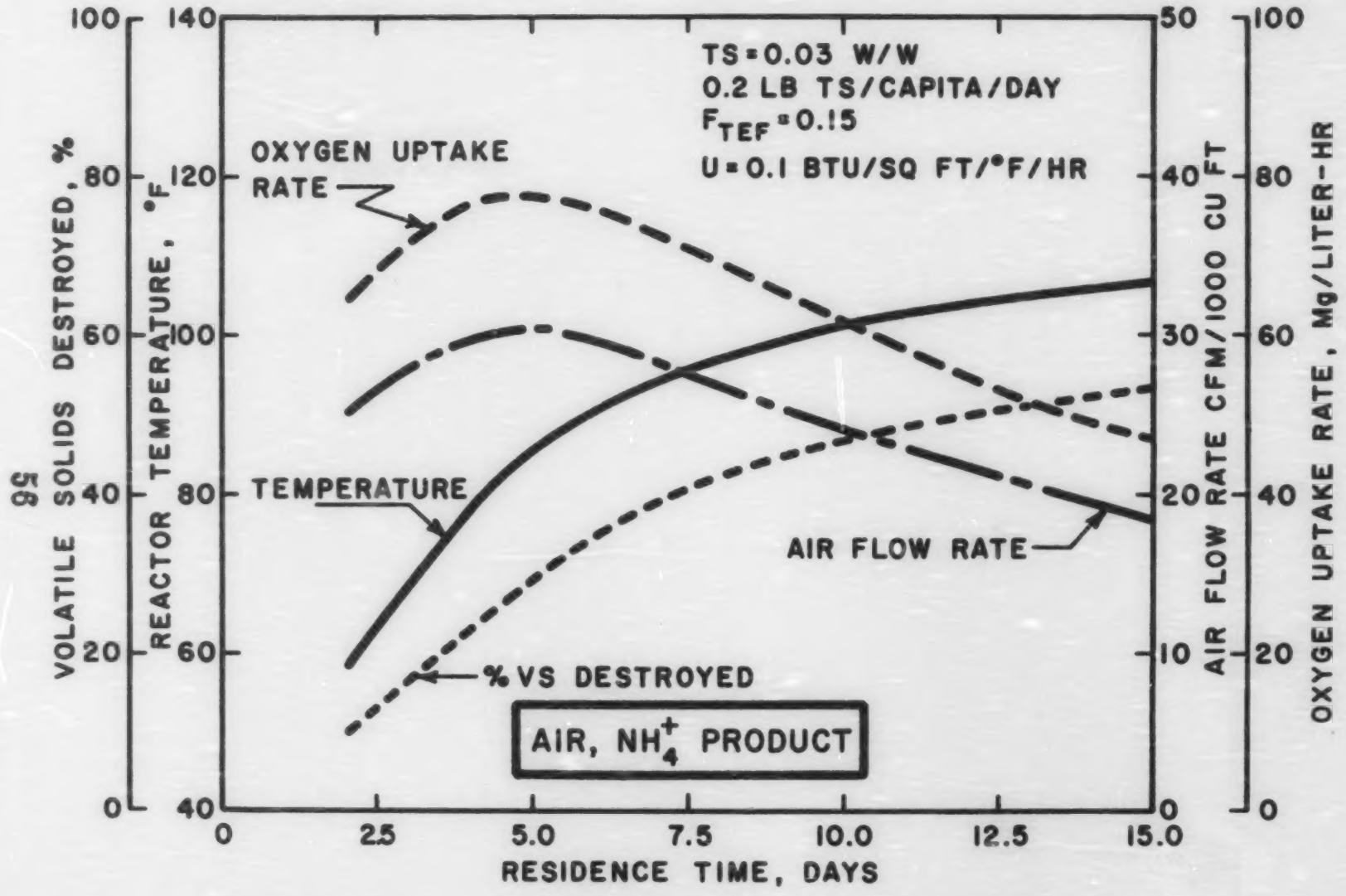

FIGURE 12. EFFECT OF RESIDENCE TIME

truction of the additional volatile solids. The mass flow rate of 1,400 lb/day of volatile solids corresponds to the 3 percent total solids and 0.2 lb of total solids PCPD previously illustrated in Figure 12. Increasing the mass flow rate of volatile solids from 1,400 to 2,100 lb/day results in an increase in reactor temperature from 102° F to 114° F with a corresponding increase in the percentage of volatile solids destroyed from 47 to 50 percent. In this instance, the addition of ground garbage to the reactor is beneficial in that it results in a higher quality digested sludge. In this respect, the process appears to be an attractive alternate for the combined treatment of garbage and sewage sludge. However, it should be noted that required oxygen uptake rates increase with increasing mass flow rate of volatile solids thus again emphasizing the importance of providing a good oxygen transfer system.

Only a moderate amount of insulation is necessary for the process to be self-sustaining at elevated temperatures (Figure 16). For comparison, the overall heat transfer coefficient for a 12 inch concrete wall with airspace insulation is 0.24 BTU/sq ft/°F/hr (54) and is 0.08 BTU/sq ft/°F/hr for a 12 inch concrete wall with 3 inches of fiber glass insulation.

Nitrification. The effect of the conversion of organic nitrogen to nitrate instead of to ammonia is illustrated in Figure 17. The amount of additional heat liberated is small and results in only a slight increase in temperature as compared to the case where the organic nitrogen is converted to ammonia. For example, the oxidation of one pound of volatile solids with an oxygen equivalent of 1.5 lb O_2/lb VS results in the production of 9,150 BTU. If the fraction of nitrogen in this

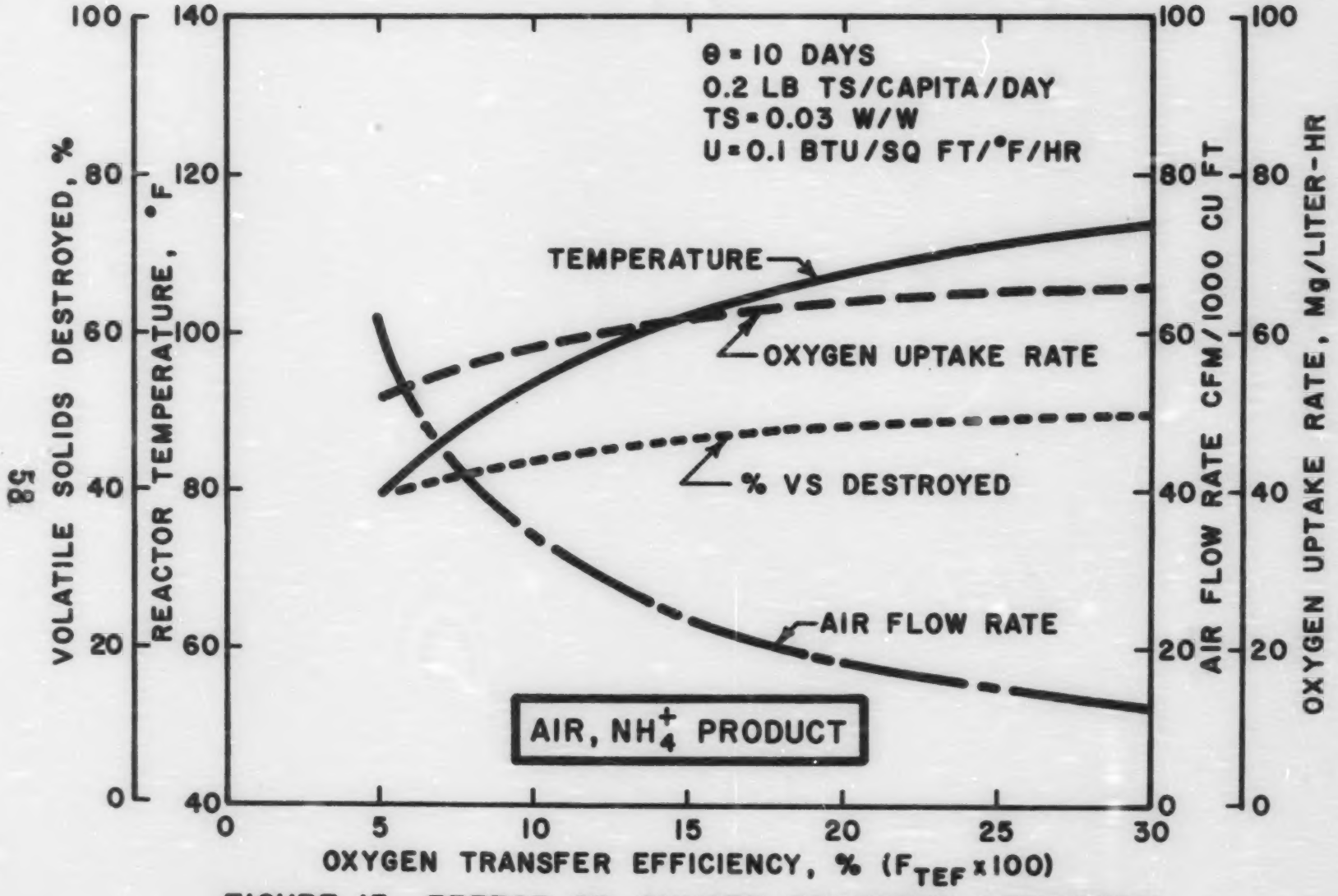

FIGURE 13. EFFECT OF OXYGEN TRANSFER EFFICIENCY

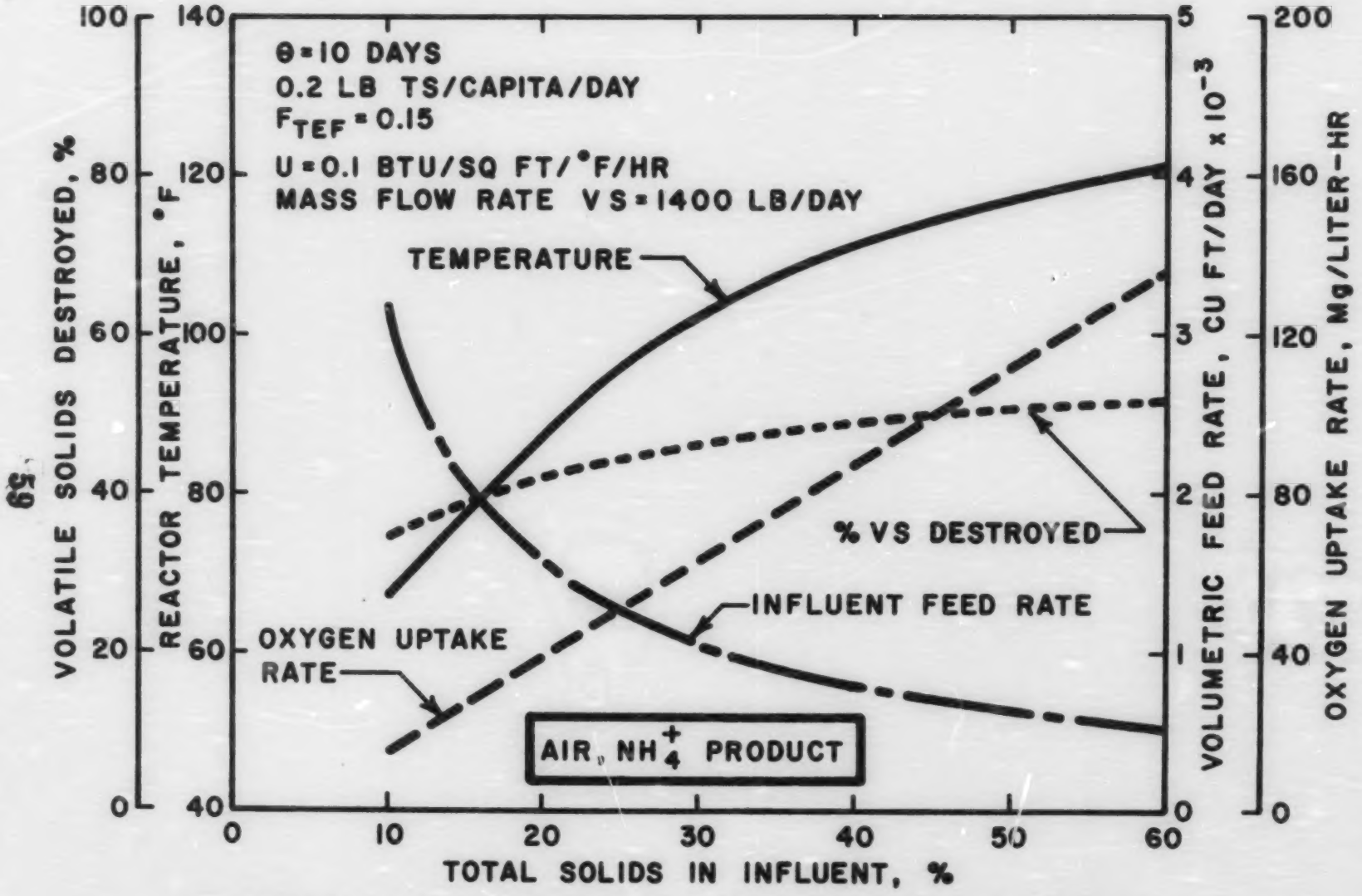

FIGURE 14. EFFECT OF THICKENING INFLUENT

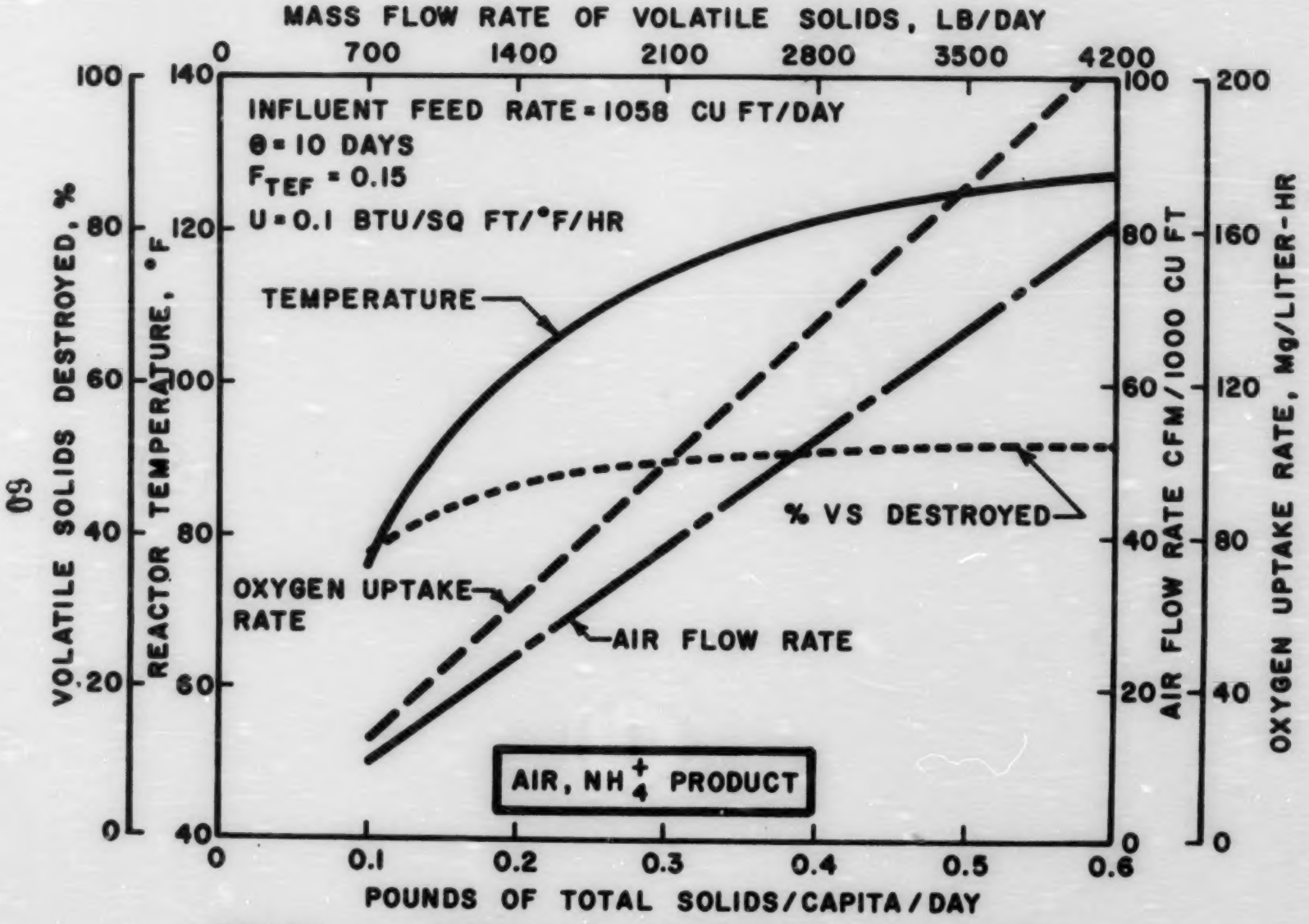

FIGURE 15. EFFECT OF INCREASING MASS FLOW RATE OF VOLATILE SOLIDS

pound of volatile solids was 0.05 and if all of this was converted to nitrate instead of to ammonia, the additional heat liberated would only be 550 BTU. However, nitrification results in a considerable increase in the oxygen uptake rate, which once again emphasizes the importance of providing good gas transfer.

Although the oxidation of ammonia to nitrate may be of significance for mesophilic aerobic digesters operated at long residence times, it may not be significant for thermophilic aerobic digesters operated at lower residence times. Although rates of nitrification could increase as temperature increases, the transfer of ammonia from the liquid phase into the gas phase would also increase with temperature and could result in low concentrations of both ammonia and nitrate in the liquid phase. Additional research is needed in this area since it is conceivable that thermophilic aerobic digestion could remove nitrogen from the sludge by transferring ammonia nitrogen from the liquid to the gas phase.

High Purity Oxygen as Influent Gas. As the mass flow rate of volatile solids into the reactor increases, there is a corresponding increase in the required oxygen uptake rates as shown in Figure 15 where oxygen uptake rates vary from 63 mg/liter/hr at a mass flow rate of volatile solids of 1,400 lb/day to 162 mg/liter/hr at a mass flow rate of 2,800 lb/day. Figure 12 also shows that oxygen uptake rates increase up to some maximum as residence time decreases. Although these rates are higher than those normally encountered in the activated sludge process, they should be attainable at mesophilic temperatures by the use of turbine aerators. Unfortunately, oxygen transfer rates in high solids, high temperature, biological processes have received little attention and the possibility exists that either the hydraulic or organic loading rate to a thermophilic aerobic digester could be limited by the

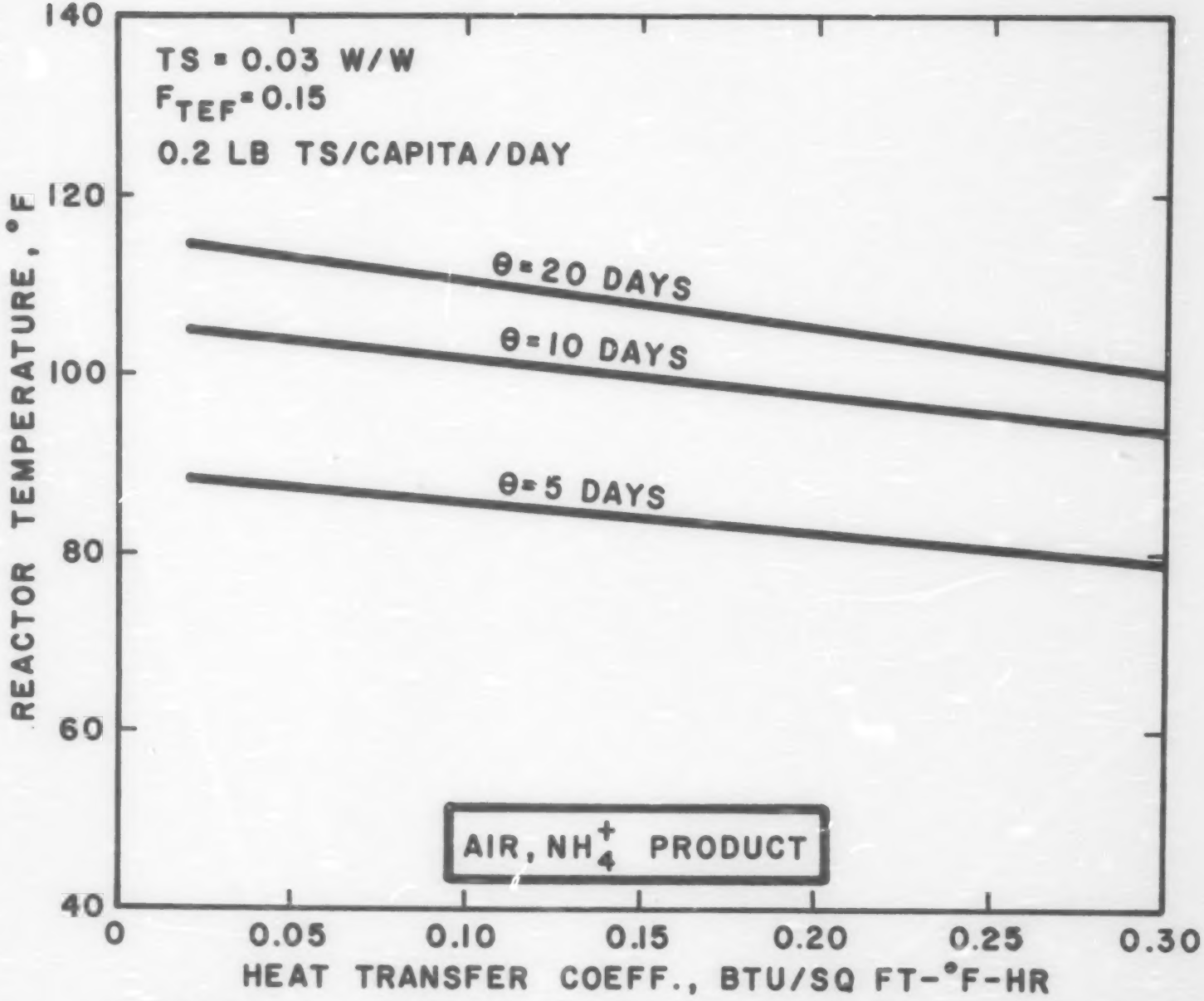

FIGURE 16. EFFECT OF HEAT TRANSFER COEFFICIENT

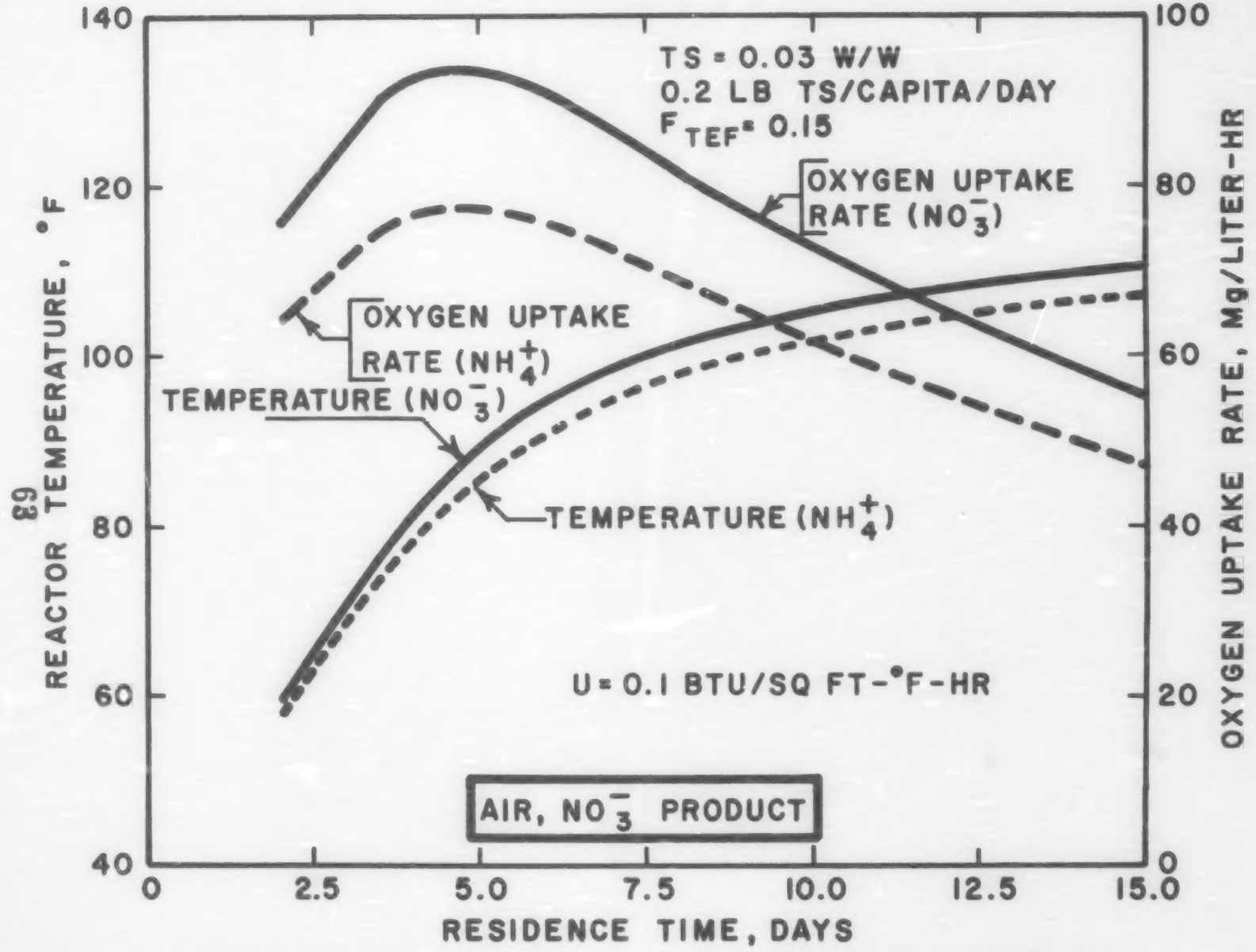

FIGURE 17. OXIDATION OF NITROGEN TO NITRATE

abiiity to transfer oxygen from the gas to the liquid phase. Although the mass transfer coefficient for oxygen transfer will increase with increasing temperature, this may be more than offset by the decreased solubility of oxygen at higher temperatures which can decrease the driving force available.

The use of high purity oxygen in the activated sludge process (55) has recently (1971) received considerable attention and appears attractive for the thermophilic aerobic digestion process since it would give higher driving forces for oxygen transfer. However, another and perhaps even more important advantage of using high purity oxygen in thermophilic aerobic digestion would be the higher temperatures and higher volatile solids destruction attainable. The water vapor carried out by the nitrogen in air would be eliminated thus decreasing latent heat losses for a given temperature. This is illustrated in Figure 18 where high purity oxygen and air are compared as influent gases for an oxygen transfer efficiency of 0.15. At a residence time of ten days, the reactor temperature attained using oxygen is 127° F as compared to 102° F for the use of air. The associated volatile solids destructions are 52 and 47 percent, respectively. The advantage of using oxygen would be even more marked if gas recycle was practiced to increase oxygen transfer efficiency as is usually the case in high purity oxygen processes. The use of high purity oxygen could also increase reaction rates by permitting a deeper penetration of dissoved oxygen into the solid particles.

Although the use of high purity oxygen for thermophilic aerobic digestion by itself might not be economically justified, it should be practical in those instances where oxygen is also to be used in the activated sludge process. The capital cost of the oxygen production

unit could then be shared between thermophilic aerobic digestion and the activated sludge process thus taking advantage of the economics of scale.

DISCUSSION

Basic theory and simulation studies show that the thermophilic aerobic digestion process may possess significant advantages over the corresponding mesophilic process and can be self-sustaining with respect to temperature. The process has significant potential for the treatment of wastewater sludges either alone or mixed with garbage. The use of high purity oxygen as an influent gas appears attractive, especially in those instances where high purity oxygen is to be used in the activated sludge process and the capital cost of the oxygen production unit can be shared.

The simulation studies which have been presented are based on steady state models and therefore cannot be used to predict process performance during start-up or under transient conditions resulting from changes in process inputs or operation. Start-up procedures and process stability are important in evaluating any new process and this is especially true for biological wastewater treatment processes where start-up periods are usually long and inputs may be highly variable. Kambhu and Andrews (10) have studied the dynamics of the thermophilic aerobic digestion process using a preliminary dynamic model with process simulation on the digital computer. These preliminary simulations indicated that the process is sensitive to sudden changes in the total solids concentration and to changes in the air flow rate. A sudden decrease in the total solids concentration or a sudden increase in the air flow rate could result in significant decreases in reactor temperature and per-

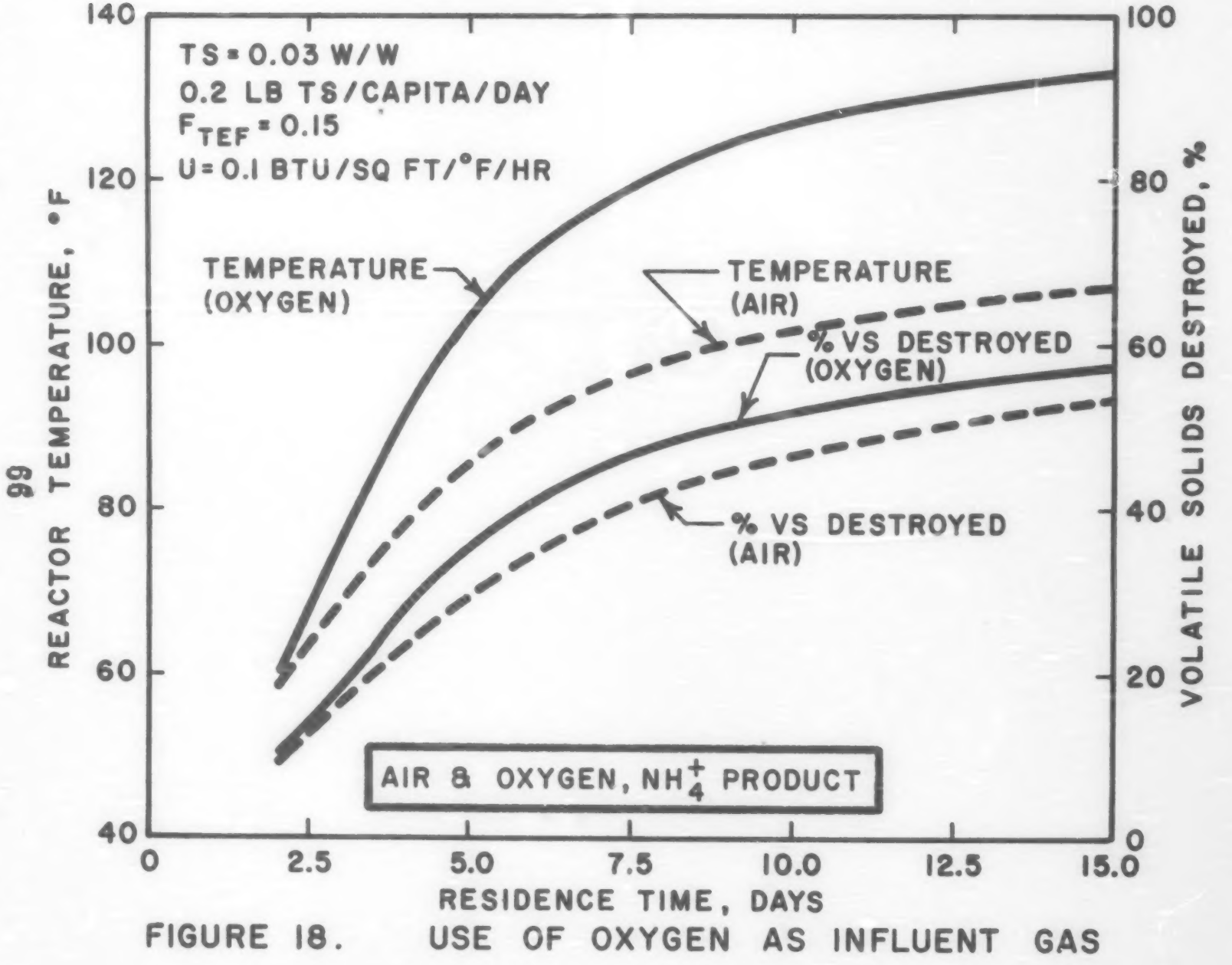

FIGURE 18. USE OF OXYGEN AS INFLUENT GAS

centage of volatile solids destroyed. This indicates the need to avoid pumping dilute sludges and the importance of careful control of the gas flow rate to the reactor. These preliminary simulations are only of qualitative significance since they did not include the effects of many important dynamic variables such as microbial time delay, organism death, or shifts in microbial population which may occur with changes in temperature. Considerable additional research will be needed to develop a dynamic model of the process for use in investigating start-up and process stability.

The next step in the development of the thermophilic aerobic digestion process should be the construction and operation of a pilot unit in the field. This would serve to test the general validity of the mathematical model and indicate needed modifications. The pilot reactor should be of sufficient size to permit scale-up to a full size unit. Different materials, such as sludge from primary settling tanks, activated sludge, and mixtures of these with ground garbage should be used as influent feeds to the reactor. Provisions should be made for the use of either air or high purity oxygen as the influent gas.

Numerical values for such important parameters as the reaction rate coefficient and fraction of volatile solids which are biodegradable should be determined at different temperatures. The effects of solids concentration and temperature on oxygen transfer efficiency and mixing requirements should be investigated. Start-up procedures, design and operational criteria, and process economics should be evaluated.

SUMMARY AND CONCLUSIONS

A new process, thermophilic aerobic digestion, has been proposed for the treatment of wastewater sludge either alone or mixed with gar-

bage. The major reactions involved in the process have been presented, discussed, and simplified into an overall net reaction for the determination of the basic stoichiometric, thermochemical, and kinetic relationships. Volatile solids destruction, oxygen utilization, and carbon dioxide production are related stoichiometrically for both ammonia and nitrate as products of organic nitrogen oxidation. A simple procedure has been presented for determining the thermochemistry of the net reaction by relating heat production to the oxygen equivalent or COD of the organic solids. As a first approximation, the rate of oxidation of the biodegradable volatile solids is considered to be first order with respect to the biodegradable volatile solids concentration. The reaction rate coefficient is expressed as a function of temperature by using a simplification of the Arrhenius equation which permits the reaction rate coefficient to increase up to an optimum and then decrease rapidly as temperature increases. A steady state mathematical model for the process has been developed by applying material and heat balances to a continuous-flow, complete-mixing reactor using the basic stoichiometric, thermochemical, and kinetic relationships.

Simulation studies based on the model show that sufficient heat can be generated through biological activity so that the process will operate autothermally at temperatures considerably higher than ambient. The difference in process temperature attained by considering the conversion of organic nitrogen to either ammonia or nitrate is small; however, oxygen utilization rates are significantly higher for nitrate as a product. Higher temperatures and increased volatile solids destruction may be obtained by:

1. Increasing residence time.
2. Increasing oxygen transfer efficiency.

3. Using thickeners to increase the concentration of solids in the influent sludge.

4. Increasing the mass flow rate of volatile solids to the reactor by the addition of ground garbage.

5. Use of high purity oxygen.

The simulation studies indicate that the process has significant potential for the treatment of wastewater sludges either alone or mixed with ground garbage and pilot plant studies would be justified. The use of high purity oxygen for the process has a dual advantage in comparison with air of higher driving forces for oxygen transfer and autothermal operation at higher temperatures. The use of high purity oxygen would be attractive when it is also used in the activated sludge process and the capital cost of the oxygen production unit can be shared between the two processes.

The model should not be used for quantitative design or operation since it has not been verified in the field and undoubtedly will require modification as data are obtained. However, it should serve as a valuable framework for these modifications and be of assistance in planning and conducting pilot plant studies. Additional research is needed to develop a dynamic model of the process for use in investigating start-up and process stability.

GLOSSARY

A	surface area of reactor, sq ft
A_H	absolute humidity, lb H_2O vapor/lb dry air
(BVS)	concentration of biodegradable volatile solids, lb/cu ft
C_1, C_2	temperature coefficients
C_{PG1}	specific heat of dry effluent gas, BTU/lb/^oF
C_{PH2O}	specific heat of water vapor, BTU/lb/^oF
C_{PL}	specific heat of sludge, BTU/lb/^oF
D	diameter of reactor, ft
D_{CO2}	density of dry carbon dioxide, lb/cu ft
D_{G1}	density of dry effluent gas, lb/cu ft
D_{GO}	density of dry influent gas, lb/cu ft
D_{H2O}	density of water vapor, lb/cu ft
D_L	density of sludge, lb/cu ft
D_{O2}	density of dry oxygen at STP
F_{BVS}	fraction of volatile solids that are biodegradable
F_N	fraction of nitrogen in the biodegradable volatile solids
F_{O2O}	fraction of oxygen (by volume) in dry influent gas
F_{TEF}	oxygen transfer efficiency
F_{VS}	fraction of total solids that are volatile
F_{VSD}	fraction of volatile solids destroyed
h	heat of combustion, calories/gram
H_A	rate of heat loss to surroundings, BTU/day
H_B	rate of heat production by biological oxidation of BVS, BTU/day
H_L	rate of net heat loss in effluent sludge, BTU/day
H_M	rate of heat input from mixing and gas supply, BTU/day
$(HP)_V$	horsepower input per unit volume of reactor, HP/cu ft

H_S	rate of net sensible heat loss in effluent gas, BTU/day
H_V	rate of heat loss as latent heat in water vapor, BTU/day
K_T	reaction rate coefficient, $days^{-1}$, at temperature T
K_{TR1}	reaction rate coefficient, $days^{-1}$, at temperature T_{R1}
(NBVS)	concentration of nonbiodegradable volatile solids, lb/cu ft
$(OE)_C$	oxygen equivalent of biodegradable volatile solids for ammonia as product, lb O_2/lb BVS
PCPD	per capita per day
P_{H2O}	partial pressure of water vapor, mm Hg
P_T	total pressure of wet gas in effluent, mm Hg
Q_{G1}	effluent dry gas flow rate at STP, cu ft/day
Q_{GO}	influent dry gas flow rate at STP, cu ft/day
Q_L	sludge flow rate to reactor, cu ft/day
R	degree of reduction
$(R)_{O2U}$	rate of oxygen utilization in reactor, lb/day
STP	standard temperature and pressure, one atmosphere, 60^oF
t	time, days
T	temperature, ^oC
T_A	temperature, ^oK
T_{G1}	temperature of effluent gas, ^oF
T_{GO}	temperature of influent gas, ^oF
T_{L1}	temperature of effluent sludge, ^oF
T_{LO}	temperature of influent sludge, ^oF
T_{R1}, T_{R2}	reference temperatures, ^oC
(TS)	concentration of total solids, lb/cu ft
U	overall heat transfer coefficient, BTU/sq ft/hr/^oF
V	reactor volume, cu ft
(VS)	concentration of volatile solids, lb/cu ft

o	subscript denoting influent to reactor
1	subscript denoting effluent from reactor
θ	reactor residence time, days

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